

Petrology of Metamorphosed  
Chromite-Bearing Ultramafic Rocks  
from the Red Lodge District,  
Montana

U.S. GEOLOGICAL SURVEY BULLETIN 1626-B





Chapter B

# Petrology of Metamorphosed Chromite-Bearing Ultramafic Rocks from the Red Lodge District, Montana

By PATRICIA J. LOFERSKI

Petrography, mineral chemistry, and  
whole-rock geochemistry of upper  
amphibolite facies chromite-bearing  
ultramafic rocks

U.S. GEOLOGICAL SURVEY BULLETIN 1626

CONTRIBUTIONS TO THE GEOLOGY OF MINERAL DEPOSITS

DEPARTMENT OF THE INTERIOR  
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY  
Dallas L. Peck, Director



UNITED STATES GOVERNMENT PRINTING OFFICE: 1986

---

For sale by the Distribution Branch, U.S. Geological Survey,  
604 South Pickett Street, Alexandria, VA 22304

**Library of Congress Cataloging in Publication Data**

Loferski, Patricia J.

Petrology of metamorphosed chromite-bearing ultramafic rocks  
from the Red Lodge District, Montana.

(Contributions to the geology of mineral deposits) (U.S. Geo-  
logical Survey bulletin; 1626-B)

Bibliography: p. B 32

Supt. of Docs. no.: I 19.3:1626-B

1. Rocks, Ultrabasic. 2. Chromite—Montana—Red Lodge Re-  
gion. I. Title. II. Series. III. Series: U.S. Geological Survey  
bulletin; 1626-B.

QE75.B9 no. 1626-B 557.3s [553.4'643] 84-600179  
[QE462.U4]

# CONTENTS

Abstract	<b>B1</b>
Introduction	<b>B1</b>
Chromite production	<b>B1</b>
Regional setting	<b>B2</b>
Metamorphism	<b>B3</b>
Field occurrence and sampling	<b>B3</b>
Methods	<b>B3</b>
Petrography	<b>B3</b>
Silicates	<b>B4</b>
Oxides	<b>B9</b>
Sulfides	<b>B11</b>
Mineral chemistry	<b>B11</b>
Olivine	<b>B11</b>
Orthopyroxene	<b>B12</b>
Clinopyroxene	<b>B12</b>
Amphibole	<b>B12</b>
Chlorite	<b>B12</b>
Phlogopite	<b>B14</b>
Serpentine	<b>B14</b>
Chromite	<b>B14</b>
Segregated chromite	<b>B17</b>
Accessory chromite	<b>B18</b>
Contact metamorphism	<b>B20</b>
Geochemistry	<b>B21</b>
Petrogenesis	<b>B23</b>
Formation and post-emplacement history	<b>B29</b>
Economic geology	<b>B29</b>
Conclusions	<b>B31</b>
References	<b>B32</b>

## FIGURES

1. Map of the Red Lodge chromite district **B2**
2. Geologic map of the eastern Beartooth Mountains showing the location of the study area **B2**
3. Photomicrograph of hornblende rim around chromite in a diopside porphyroblast **B5**
4. Photomicrographs of serpentine textures **B9**
5. Photomicrograph of segregated chromite from assemblage 2 **B10**
6. Photomicrograph of recrystallized chromite **B11**
7. Photomicrograph of ragged accessory chromite from assemblage 5 **B11**
8. Photomicrograph of chromite from assemblage 3 **B11**
9. Photomicrograph of ferritchromite+chlorite(?) alteration of Al-rich chromite from assemblage 1 **B12**

10. Compositional plot of pyroxene analyses on pyroxene quadrilateral **B14**
11. Compositional plot of FeO versus MgO weight percent in amphiboles from ultramafic rocks and from amphibolites **B14**
12. Plot of serpentine compositions with respect to SiO<sub>2</sub>-MgO-FeO in weight percent **B16**
13. Compositions of segregated and accessory chromite **B16**
14. Compositions of segregated chromite from the various assemblages **B19**
15. Compositions of segregated chromite from the various deposits **B22**
16. Compositions of accessory chromite **B23**
17. Chromite compositions with respect to Cr-Al-Fe<sup>3+</sup> **B26**
18. Variation diagrams of selected oxides versus SiO<sub>2</sub> in ultramafic rocks and amphibolites **B27**
19. Compositional plots of amphibolites **B29**

#### TABLES

1. Assemblages in the Red Lodge ultramafic rocks **B4**
2. Modal mineralogy of the Red Lodge ultramafic rocks **B6**
3. Representative microprobe analyses of olivine, orthopyroxene, and clinopyroxene **B13**
4. Representative microprobe analyses of amphibole **B15**
5. Representative microprobe analyses of chlorite and phlogopite **B17**
6. Representative microprobe analyses of serpentine **B18**
7. Representative microprobe analyses of segregated chromite **B20**
8. Representative microprobe analyses of accessory chromite **B24**
9. Ferritchromite analyses from other locations **B25**
10. Chemical analyses of ultramafic rocks near monzonite dike at the Highline claim **B25**
11. Chemical and normative analyses of Red Lodge rocks, and comparative averages **B28**
12. Trace-element analyses of Red Lodge ultramafic rocks **B30**

# Petrology of Metamorphosed Chromite-Bearing Ultramafic Rocks from the Red Lodge District, Montana

By Patricia J. Loferski

## Abstract

The chromite deposits near Red Lodge, Mont., occur in small ultramafic lenses that are enclosed in remnants of a metasedimentary-metavolcanic sequence that in turn are surrounded by Archean granitic gneiss. The stratiform versus podiform origin of the deposits has been debated in the past because amphibolite to granulite facies metamorphism at about 2,800 m.y. ago has obscured most primary features.

Samples collected from various ultramafic lenses show that the most common rocks are (1) serpentinites and (2) those composed of hornblende±clinopyroxene. Less common assemblages are hornblende+orthopyroxene±olivine, talc+carbonate±phlogopite, and backwall rocks.

Chromite occurs as a ubiquitous accessory mineral and as local segregated lenses. Optically, much of the chromite is homogeneous; some chromite grains have magnetite and rare ferritchromite rims. Ferritchromite+chlorite(?) intergrowths occur in some accessory aluminum-rich chromite. Compositionally, some segregated chromite corresponds to stratiform-type magmatic chromite; other segregated and most accessory chromite show metamorphic iron enrichment and magnesium and aluminum depletion, an alteration trend most pronounced in the accessory chromite.

Major- and minor-element geochemistry shows continuous variation from mafic to ultramafic compositions. No evidence of metasomatism was found; thus, the various silicate assemblages were formed from a variety of rocks, probably including dunite, peridotite, feldspathic peridotite, and gabbro. The ultramafic bodies are probably tectonically disrupted fragments of a stratiform complex, and this hypothesis is consistent with the chromite compositions and textures, the Archean age of the rocks, and the geologic environment of the deposits, all of which are similar to stratiform deposits.

Most of the known chromite ore in the district has been mined. The economic potential of the remaining deposits is problematic because of (1) the low concentration (typically 5–15 percent) of chromite in most rocks; (2) high-iron metamorphic chromite compositions; and (3) ferritchromite-chlorite(?) intergrowths formed during chromite alteration that may cause milling problems. Contents of cobalt, nickel, and the platinum-group elements in the ultramafic rocks are far below present economic limits.

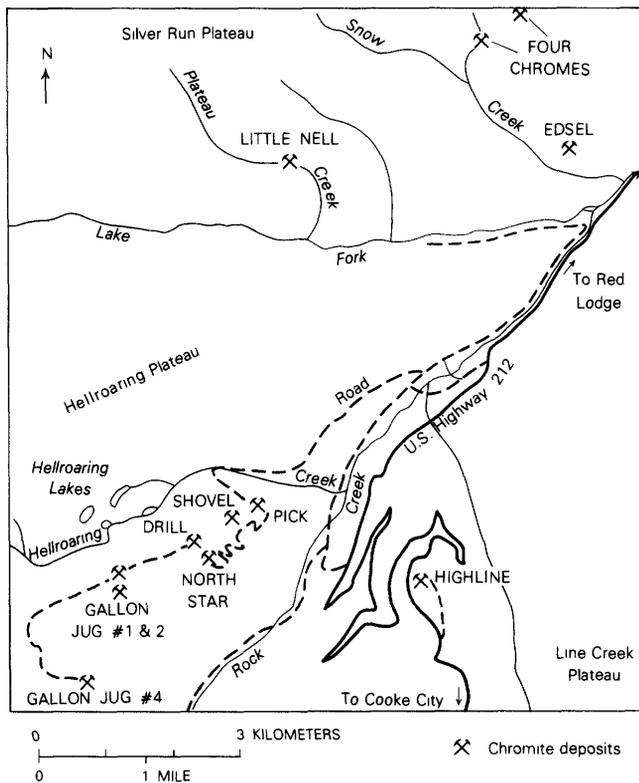
If the ultramafic rocks are fragments of a disrupted stratiform complex, other fragments with local chromite concentrations may be buried at depth. However, those undiscovered deposits would have been subjected to the same high-grade metamorphism, and therefore would have the same characteristics as those exposed at the surface.

## INTRODUCTION

Chromite occurs as a ubiquitous accessory mineral and as local concentrations in small lenses of ultramafic rocks that are scattered along the northern front of the Beartooth Mountains of Montana and Wyoming. In the Red Lodge district, the ultramafic rocks and the enclosed chromite were metamorphosed to upper amphibolite and locally to granulite facies about 2,800 m.y. ago (Gast and others, 1958; Simons and others, 1979), and to greenschist facies about 1,600–1,800 m.y. ago (Nunes and Tilton, 1971; Rowan and Mueller, 1971). Whether the deposits are stratiform or podiform has been debated since the report by James (1946) because primary features have largely been obscured by the high-grade metamorphism. This work was undertaken to characterize the effects of the metamorphism on the ultramafic rocks in general, and on the chromite in particular, to determine how the high-grade metamorphism has affected the economic potential of the chromite deposits, and to determine their petrogenesis.

## CHROMITE PRODUCTION

Chromite was discovered in the Red Lodge district in 1916 in the Four Chromes deposit on Silver Run Plateau (fig. 1). Pods and lenses of chromite were mined from open pits during the early 1940's from deposits on Hellroaring and Line Creek Plateaus, and total production was about 61,600 metric tons of chromite ore (Simons and others, 1979). The crude ore averaged about 24–40 percent Cr<sub>2</sub>O<sub>3</sub>,

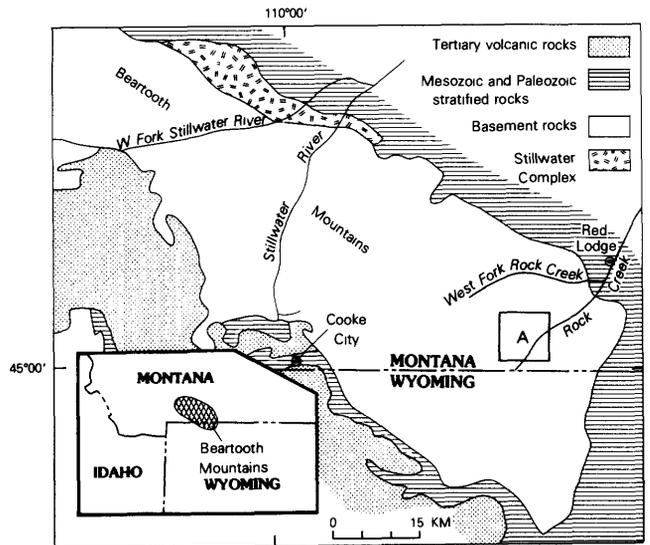


**Figure 1.** Red Lodge chromite district showing deposits on Hellroaring, Silver Run, and Line Creek Plateaus, modified from Simons and others, 1979.

and Cr/Fe ratios were about 0.59–1.60 (James, 1946). No production was recorded from the deposits on Silver Run Plateau.

## REGIONAL SETTING

The Beartooth Mountains form a northwest-trending roughly rectangular block, about 65 by 115 km, that was uplifted along high-angle reverse faults during the Laramide orogeny (fig. 2). The core of the range consists mainly of Archean granitic gneiss variously interpreted to have an igneous (James, 1946), metamorphic (Eckelmann and Poldervaart, 1957; Simons and others, 1979), or combined metamorphic, metamorphic, and igneous origin (Butler, 1969). Minor migmatites, pegmatites, and orbicular rocks are also present. The ultramafic rocks form concordant lenses in remnants of an interlayered metasedimentary-metavolcanic sequence that in turn occur as isolated roof pendants in the granitic gneiss (James, 1946). The interlayered sequence consists of interbedded quartzite, amphibolite, biotite schist, and banded ironstone (Eckelmann and Poldervaart, 1957; Casella, 1964; Simons and others, 1979). The Stillwater Complex, a stratiform mafic-ultramafic igneous intru-



**Figure 2.** Geologic map of the eastern Beartooth Mountains. Location of the study area is outlined (A). The map is modified from Page, 1979.

sion, crops out on the northern front of the Beartooths approximately 40 km northwest of the present study area. Mafic dikes of several ages and felsic porphyry dikes and plugs of Tertiary age cut the older rocks throughout the area (Eckelmann and Poldervaart, 1957; Casella, 1969; Simons and others, 1979). Paleozoic and Mesozoic sedimentary rocks occur along most of the perimeter of the range, and Tertiary volcanic rocks occur on the west and southwest sides.

The Red Lodge ultramafic rocks are part of a generally northwest trending belt of small ultramafic lenses, which approximately parallels the northern edge of the Beartooth Mountains (Hess, 1955). The ultramafic lenses in the study area range in size from a few tens of meters to about 360 m by 45 m; the best exposures are found at edges of plateaus at elevations of about 3,000 m. James (1946) investigated the chromite deposits in the Red Lodge area, with emphasis on their structure and economic geology. His detailed geologic maps were used in the present study.

Various theories have been proposed concerning the origin and emplacement of the ultramafic rocks. Most workers believe that they were emplaced as solid bodies into the plastic country rocks during regional metamorphism (James, 1946; Poldervaart, 1958) and that the ultramafic rocks possibly were derived by the disruption of a stratiform ultramafic sheet (Skinner, 1969). Some of the ultramafic lenses appear to have been dikes, which were later pulled apart by flowage (James, 1946; Casella, 1969). Amphibolites associated with many of the ultramafic lenses are generally considered to have been derived from tholeiitic basalt (Armbrustmacher and Simons, 1977; Simons and others, 1979).

## METAMORPHISM

Peak metamorphic conditions in the eastern Beartooths were estimated by previous workers to be from upper amphibolite to granulite facies. Eckelmann and Poldervaart (1957) estimated a peak metamorphic temperature of 500°–600°C on the basis of the mineral assemblages in amphibolites, ironstones, biotite schists, and ultramafic rocks. Casella (1969) estimated metamorphic conditions at the upper amphibolite facies with temperatures greater than 550°C and low pressure. Skinner (1969), on the basis of the presence of orthopyroxene in the rocks, estimated upper amphibolite to granulite facies metamorphism of ultramafic rocks in the nearby Highline Trail Lakes area. However, Evans (1977) showed that orthopyroxene may be present in the upper amphibolite facies.

Calculations based on the the olivine-spinel geothermometer (Irvine, 1965; Jackson, 1969; Evans and Frost, 1975) yield temperatures of about 600°–650°C for two samples of the Red Lodge ultramafic rocks (Loferski and Lipin, 1983). Those temperatures correspond to those of the upper amphibolite facies.

## FIELD OCCURRENCE AND SAMPLING

Samples were collected from open pits and outcrops at the Pick, Shovel, North Star, Drill, and Gallon Jugs 1, 2, and 4 claims on Hellroaring Plateau; the Highline claim on Line Creek Plateau; and the Four Chromes deposit on Silver Run Plateau (see fig. 1). Both accessory chromite and chromite ore from mine dumps were sampled. Samples collected by H. L. James in 1942 from some of the deposits listed above and from the Edsel and Little Nell deposits on Silver Run Plateau were also analyzed. The amphibolites near the contacts with the ultramafic lenses were sampled at the Drill, Highline, and Gallon Jug 4 claims. A 9-m-wide monzonite porphyry dike intrudes the ultramafic lens at the Highline open pit, and samples were taken at various distances from the dike to check for contact metamorphic effects.

Within individual lenses, the rocks are highly sheared and disrupted, and faulting is common. Felsic veins and dikes occur throughout the area, especially at the Drill claim. What appeared to be igneous layering was observed in only one area of the North Star open pit, where chromite bands are interlayered with serpentinite. The thickness of the layers ranges from several centimeters to about 1 m. The layers are parallel to the boundaries of the ultramafic body and to the foliation in the country rock. Other layering seen in the outcrops and in thin sections is metamorphic in origin.

Contacts with the country rocks are exposed in the three largest open pits: Drill, North Star, and Highline. A sheared zone, ranging from a meter to a few meters in width, was observed at the contact.

Felsic veins and dikes in the ultramafic bodies are common, especially at the Drill claim. Metasomatic effects, typically showing the formation of hornblende along the contacts, can be seen both on the scale of an outcrop and on the scale of a thin section.

## METHODS

Fifty-seven thin sections, including 5 amphibolites, and 12 polished sections were studied. Standard optical techniques were used in both reflected and transmitted light. Point counts were performed on most of the thin sections and polished sections, with at least 1,000 points for each sample. In other samples, modal estimates and determinative charts of Terry and Chillingar (1955) were used.

Electron microprobe analyses were done on individual mineral grains, and the method of Bence and Albee (1968) was used to reduce data. For all mineral species except amphibole and chromite, Fe is reported as total FeO. Fe<sup>3+</sup>, as well as minimum and maximum values of Fe<sub>2</sub>O<sub>3</sub>, was estimated for amphiboles using the method of Papike and others (1974). Calculation of Fe<sup>3+</sup> in spinels was based on ideal spinel stoichiometry.

Selected samples were analyzed by means of X-ray diffraction analyses to identify serpentine polymorphs and to check for brucite. Whole-rock major- and selected trace-element chemical analyses were obtained for many of the samples.

## PETROGRAPHY

Six different silicate assemblages were recognized in the ultramafic rocks, and each individual ultramafic lens is dominated by one particular assemblage (table 1). The amount of chromite varies between samples within assemblages 1, 3, 5, and 6, whereas most samples of assemblages 2 and 4 are chromitites.

Some general characteristics of the various assemblages are as follows. Assemblages 1 through 3 preserve the relict high-grade silicates—amphibole, pyroxene, and olivine—all of which have undergone various degrees of retrograde alteration. In contrast, the silicates in assemblages 4 and 5 are mainly the retrograde minerals—serpentine, talc, chlorite, phlogopite, and carbonate minerals. By far the most common type of retrograde alteration is serpentinization, and the most common assemblage is 5, the serpentinites. Assemblage 6 consists of blackwall rocks, formed by reaction between the ultramafic rocks and the country rocks.

Two of the assemblages, 1 and 3, show characteristic banded textures in thin sections. The assemblage 1 rocks have alternating nearly monomineralic layers, which have a maximum thickness of several grains, of hornblende, orthopyroxene, and olivine. Similar types of monomineralic

**Table 1.** Assemblages in the Red Lodge ultramafic rocks

[Minerals listed in decreasing order of abundance; characteristic minerals capitalized; retrograde minerals in parentheses. Abbreviations used are hbd, hornblende; opx, orthopyroxene; serp, serpentine; chr, chromite; tc, talc; ol, olivine; am, amphibole; chl, chlorite; phl, phlogopite; carb, carbonate minerals; cpx, clinopyroxene; pc, plagioclase; ep, epidote, bi, biotite]

Assemblage number	Assemblage mineralogy	Number of samples	Probable protolith
1.	HBD + OPX ( $\pm$ serp) + chr (+tc) $\pm$ OL	7	Harzburgite.
2.	chr + AM (+serp $\pm$ tc $\pm$ chl $\pm$ phl $\pm$ carb) $\pm$ cpx $\pm$ pc $\pm$ ep	14	Feldspar- or clinopyroxene-rich chromitite.
3.	AM + CPX ( $\pm$ serp) + chr ( $\pm$ tc $\pm$ chl)	8	Feldspathic pyroxenite, or gabbro.
4.	chr (+serp + TC $\pm$ phl) $\pm$ hbd (+CARB)	5	Chromitite.
5.	(SERP) + chr $\pm$ ol ( $\pm$ chl $\pm$ tc $\pm$ carb $\pm$ phl) $\pm$ am $\pm$ opx	24	Dunite.
6.	Blackwall: am+bi $\pm$ pc, and am+chl $\pm$ pc	5	

layering have been attributed by other workers to metamorphic rather than igneous processes (James, 1946; Skinner, 1969). In the Red Lodge rocks, the layering is obscured by shearing and retrograde alteration. Banding is also seen in the assemblage 3 rocks, in which layers of clinopyroxene alternate with layers of hornblende  $\pm$  chromite. The layers are as much as several grains thick, and are metamorphic in origin.

Modal analyses of all the rocks are shown in table 2. The general characteristics of each mineral species are as follows.

### Silicates

The amphibole, typically hornblende that is pale green to colorless in thin section, is the most widespread of the three relict high-grade silicates, and is present in samples from all the ultramafic lenses in amounts that range from 2 percent to about 90 percent of individual samples. Most commonly, it occurs as equant grains with 120° triple-grain junctions, and as short prisms, some in subparallel orientation. Coarse twins are present in a few grains. Less commonly, the amphibole occurs as porphyroblasts as long as 2 mm, and, in two assemblage 2 chromitites, it forms ragged inclusion-filled laths with sutured grain boundaries.

Zoned crystals, consisting of hornblende cores and aluminum-poor tremolite or actinolite rims, occur in three assemblage 2 samples from the Little Nell and Edsel claims. In thin sections, the zoning is seen as a pronounced difference and sharp break in the birefringence between the cores and

rims of grains, and the zonation follows the shape of the crystals.

Orthopyroxene was found in nine of the samples. It was found primarily in assemblage 1, in amounts as great as 38 percent, and in trace amounts in two serpentinites. It is present in samples from the Gallon Jug 1, Gallon Jug 4, and Highline claims. It most commonly forms sheared porphyroblasts as long as 3 mm; alteration to fine-grained talc is extensive along rims and cleavages, and patches of green hornblende are present in many grains.

Olivine, because it has been altered to serpentine, is not very abundant in the Red Lodge rocks. It was identified in six samples from assemblage 1 and in six from assemblage 5; the samples came from the North Star, Gallon Jug 1, Gallon Jug 4, Highline, and Four Chromes claims. Olivine was found in amounts that range from less than 1 percent to 17 percent, but it composes less than 5 percent of most samples. In all samples, the rims and cracks are serpentinized to various degrees, and magnetite veins occur in the serpentinized areas. Absence of undulatory extinction in the olivine grains indicates that they are not strained. A few olivine grains from assemblage 1 contain veins of dusty magnetite, which probably formed during a serpentinization event that preceded the upper amphibolite facies metamorphism. The presence of these veins in olivine indicates that the olivine is metamorphic and crystallized from pre-existing serpentine. The serpentine presently in the samples is therefore second-generation serpentine.

Clinopyroxene is present in 11 samples in amounts that range from less than 1 percent to about 70 percent. It is a characteristic mineral in assemblage 3, and it is a rare

accessory mineral in assemblages 1 and 2. It was found in samples from the Drill, Gallon Jug 2, Shovel, and Highline claims. It is pale green, and forms anhedral grains, commonly with  $120^\circ$  triple grain junctions, and ragged inclusion-filled porphyroblasts that show wavy extinction. The grain size is generally about 0.5 mm, and the length of porphyroblasts ranges from 4 or 5 mm to 1 cm. The clinopyroxene contains patches and rims of hornblende, and alteration to talc and brown cloudy material along rims and cleavages is common, and in some grains complete.

In assemblage 3, with very few exceptions, the chromite is not in direct contact with the clinopyroxene. In thin sections, the layering in the rocks is very conspicuous and striking: the chromite is confined to the hornblende layers, and the clinopyroxene layers are free of chromite. In addition, small chromite inclusions in clinopyroxene porphyroblasts are rimmed by hornblende (fig. 3). These textures suggest a reaction relationship such as:

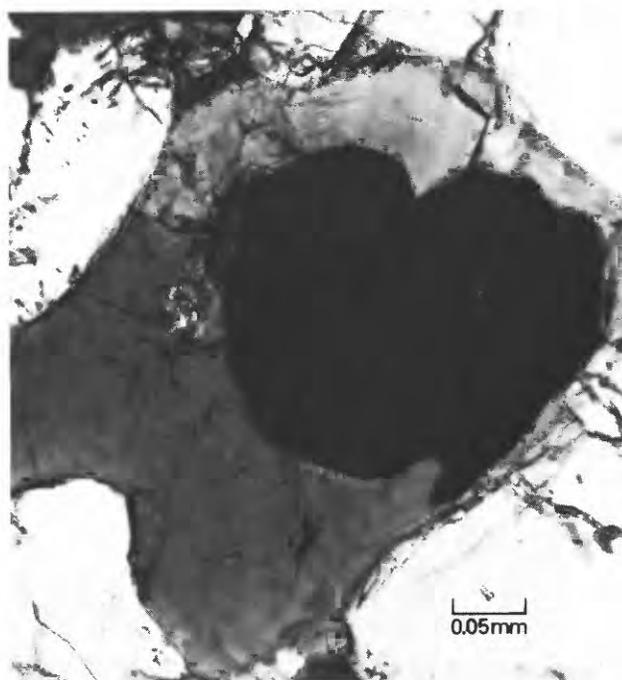
$\text{Cr-spinel} + \text{diopside} + (\text{Na, Al bearing}) \text{ fluid} \rightarrow \text{amphibole},$

which was proposed by Best (1974) and Frances (1976) to account for the presence of amphiboles in ultramafic xenoliths.

Of the retrograde minerals, serpentine is by far the most common. It was found in nearly every sample in amounts that range from trace to about 90 percent. The serpentine is variously colorless, light green, brown, or reddish brown in thin section. Some serpentinite samples contain rare islands of relict high-grade silicates, including amphibole, pyroxene, and olivine.

Serpentine minerals are useful petrogenetic indicators because they preserve a variety of textures that are characteristic of certain types of alteration. Identification of serpentine minerals based on their textures is as follows. Mesh-textured  $\alpha$ -serpentine (length fast) is generally composed of lizardite and is a retrograde texture (Cressy, 1979; Wicks and Plant, 1979), whereas hourglass-textured serpentine, although also composed of lizardite, is mainly a prograde texture (Wicks and Plant, 1979). Nonpseudomorphic  $\gamma$ -serpentine (length slow) is most commonly antigorite (Wicks and Plant, 1979), but may also be either lizardite or chrysotile. In most places, nonpseudomorphic serpentine may form either by shearing during retrograde metamorphism or by recrystallization of mesh-textured serpentine during prograde metamorphism (Wicks and Whittaker, 1977).

Serpentine textures in the Red Lodge rocks vary within and between samples. Of the pseudomorphic textures, mesh textures formed at the expense of olivine are the most common (fig. 4A), and of 11 samples, the fact that 9 contain  $\alpha$ - and 2 contain  $\gamma$ -serpentine indicates that most are composed of lizardite. The mesh rims are variously defined by (1) serpentine "veins" with or without central parting; (2) magnetite veins; (3) carbonate veins; and (4) brown to reddish-brown rims, in which the color is probably caused



**Figure 3.** Photomicrograph taken in transmitted light of hornblende rim (medium gray), enclosing chromite (black) in a diopside porphyroblast (white) from assemblage 3.

by inclusions of fine-grained iron oxides. In some samples, the mesh rims are visible only in plane polarized light; under crossed nicols the serpentine has a nonpseudomorphic texture which indicates recrystallization. Hourglass textures of  $\alpha$ -serpentine occur in three of the samples from Gallon Jug 1 and from the Highline deposits, and, as discussed above, these are the result of a prograde event. Other serpentine pseudomorphic textures include rare bastites formed from pyroxene and amphibole, in which relict cleavages are preserved in some places. Bastite-textured serpentine in thin section is colorless and free of dusty magnetite inclusions.

Isotropic serpentine was found in a few samples associated with serpentinized pyroxene, and as mesh cores in one sample from the North Star deposit.

Nonpseudomorphic textures range from interlocking to interpenetrating (as defined by Wicks and Whittaker, 1977), usually  $\gamma$ -serpentine. Such textures occur as patches in samples that also contain pseudomorphic serpentine, and as the only serpentine texture in some samples. In a few places, an original mesh texture is obliterated by later growth of nonpseudomorphic serpentine. This transition from pseudomorphic to nonpseudomorphic textures is exemplified in a sample from North Star in which radiating bundles of antigorite (determined on the basis of the texture and chemistry) have grown from the cores of brown, nearly isotropic mesh serpentine (fig. 4B). Some areas of that thin section are composed only of the mesh serpentine, other areas only of the interpenetrating (antigorite) fibers plus talc, and, in some areas, the two intergrade.

**Table 2.** Modal mineralogy of the Red Lodge ultramafic rocks

[Abbreviations used are Chr, chromite; Mt, magnetite; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Am, amphibole; Chl, chlorite; Serp, serpentine; Tc, talc; Phi, phlogopite; Carb, carbonate; Ep, epidote; Pc, plagioclase; Bi, biotite; tr, trace]

Sample Number	Chr	Mt	Ol	Opx	Cpx	Am	Chl	Serp	Tc	Phi	Carb	Ep	Pc	Bi	Assemblage
<b>Helroaring Plateau</b>															
<b>Drill</b>															
HP-1	4	1	-	-	47	3	-	45	-	-	-	-	-	-	3
HP-2	1	-	-	-	44	55	-	tr	tr	-	-	-	-	-	3
HP-3	20	tr	-	-	10	19	tr	51	-	-	-	-	-	-	3
HP-4A	23	-	-	-	17	60	-	tr	-	-	-	-	-	-	3
HP-7	2	-	-	-	56	41	-	-	1	-	-	-	-	-	3
HP-8	-	8	-	-	-	81	-	-	-	6	-	-	-	-	2
HP-32	Amphibolite														
<b>North Star</b>															
HP-9	1	tr	-	-	-	-	3	90	6	-	tr	-	-	-	5
HP-10A	70	tr	-	-	-	-	9	18	-	3	-	-	-	-	5
HP-10B	5	tr	-	-	-	-	tr	92	3	tr	tr	-	-	-	5
HP-11	10	1	17	-	-	-	tr	65	-	-	7	-	-	-	5
HP-12	10	5	-	-	-	-	7	70	-	8	-	-	-	-	5
HP-13	14	1	-	-	-	-	5	80	-	-	-	-	-	-	5
HP-31	83	tr	-	-	-	-	-	tr	9	8	tr	-	-	-	4
HJ-12-42	35	tr	10	-	-	-	-	55	-	-	-	-	-	-	5
HJ-24-42	76	tr	-	-	-	-	7	17	-	-	-	-	-	-	5
HJ-25-42	32	tr	-	-	-	-	17	51	-	-	-	-	-	-	5
<b>Gallon Jug 1</b>															
HP-17	7	-	-	-	-	-	tr	93	-	-	-	-	-	-	5
HP-18	3	2	-	-	-	-	4	91	-	-	-	-	-	-	5
HP-19	25	3	1	20	-	10	-	36	5	-	-	-	-	-	1
HP-20A	10	2	4	24	-	40	-	15	5	-	-	-	-	-	1
<b>Gallon Jug 2</b>															
HP-14	10	20	-	-	-	20	-	46	2	2	-	-	-	-	5
HP-16	-	tr	-	-	5	90	-	-	2	-	-	2	1	-	2
HJ-73-42	80	tr	-	-	-	17	1	2	-	-	-	-	-	-	2



**Table 2.** Modal mineralogy of the Red Lodge ultramafic rocks—Continued

[Abbreviations used are Chr, chromite; Mt, magnetite; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Am, amphibole; Chl, chlorite; Serp, serpentine; Tc, talc; Phl, phlogopite; Carb, carbonate; Ep, epidote; Pc, plagioclase; Bi, biotite; tr, trace]

Sample Number	Chr	Mt	Ol	Opx	Cpx	Am	Chl	Serp	Tc	Phl	Carb	Ep	Pc	Bi	Assemblage
<b>Line Creek Plateau—Continued</b>															
<b>Four Chromes</b>															
SR-1	25	-	-	-	-	44	30	-	1	-	-	-	-	-	6
SR-2	7	3	-	-	-	15	-	50	20	-	5	-	-	-	4
HJ-1-42	4	-	35	-	-	-	-	61	-	-	-	-	-	-	5
HJ-2a-42	54	tr	11	-	-	6	4	25	-	-	-	-	-	-	5
HJ-33-42	70	-	17	-	-	-	-	13	-	-	-	-	-	-	5
HJ-34a-42	44	tr	-	-	-	-	5	46	5	-	-	-	-	-	5
<b>Little Nell</b>															
HJ-80-42	41	tr	-	-	-	47	5	tr	5	-	2	-	-	-	2
HJ-81-42	68	-	-	-	-	17	9	tr	6	-	tr	-	-	-	2
HJ-84-42	77	-	-	-	-	18	2	3	-	-	-	-	-	-	2
HJ-87-42	70	tr	-	-	-	20	-	10	-	-	-	-	-	-	2
<b>Edsel</b>															
HJ-4-42	61	-	-	-	-	37	1	-	-	-	1	-	-	-	2
HJ-9-42	45	-	-	-	-	50	-	tr	5	-	-	-	-	-	2
HJ-10-42	63	-	-	-	-	30	2	5	-	-	-	-	-	-	2

Selected samples were analyzed by means of X-ray diffraction analysis, and methods of Whittaker and Zussman (1956) and Aumento (1970) were used for interpretation. One sample composed predominantly of mesh-textured  $\alpha$ -serpentine is mostly lizardite and minor antigorite. Another sample that has  $\alpha$ -serpentine mesh and hourglass textures and subordinate nonpseudomorphic  $\gamma$ -serpentine is composed of lizardite and antigorite in roughly equal amounts, and two samples of nonpseudomorphic  $\gamma$ -serpentine are composed of antigorite and subordinate lizardite. Chrysotile was not identified on the X-ray diffraction traces, but it is possible that chrysotile composes the veinlets in the samples in amounts below the detection limits of X-ray diffraction analysis.

Therefore, the textures and mineralogy indicate that most of the serpentinites are retrograde in origin, and were formed from dunite (now mesh-textured serpentine) and peridotite (now mesh-textured serpentine and bastite). Later, recrystallization produced the hourglass and nonpseudomorphic textures in some serpentinites.

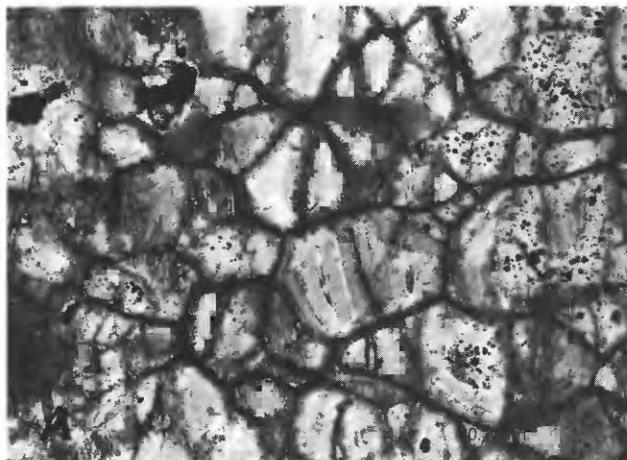
Brucite was not identified in the serpentinites, which may indicate (1) an initially low MgO/SiO<sub>2</sub> ratio; (2) introduction of SiO<sub>2</sub>; (3) removal of MgO; or (4) high CO<sub>2</sub> contents, which would react with brucite to form magnesite.

Other retrograde minerals in the Red Lodge rocks include talc, chlorite, phlogopite, and carbonate minerals; generally they occur in only minor amounts. The talc commonly forms fine-grained patches. The phlogopite forms laths, and the cleavage planes typically contain magnetite with exsolved hematite. In places, chlorite is associated with ferritchromit, and it also occurs as interstitial laths in some segregated chromites. The carbonate minerals occur in irregular patches, and as mesh rims in one serpentinite.

Epidote was found in two samples. In one assemblage 6 sample, from Highline, epidote replaces dark-green hornblende. The other sample, from assemblage 2 at Gallon Jug 2, contains rare epidote grains. Partially to completely sericitized plagioclase also is present in those samples.

In summary, the silicate minerals record the following petrogenetic sequence after formation of the original igneous parent rocks: (1) serpentinization, (2) metamorphism to at least upper amphibolite facies conditions, (3) retrograde alteration, and (4) slight prograde recrystallization of some serpentine.

A question arises about whether the six assemblages were formed at a variety of metamorphic grades. Although local differences in the peak metamorphic conditions may have existed throughout the area, neither large differences between the lenses nor progressive differences across the district were detected in the ultramafic rocks. The wide geographic distribution of orthopyroxene and the extensive occurrence of hornblende indicate conditions of the upper amphibolite facies throughout the area. At lower grades, the amphibole in metamorphosed ultramafic rocks is tremolite (Evans, 1977). Therefore, peak metamorphic grade was



**Figure 4.** Photomicrographs taken in transmitted light of serpentine textures. *A*, Pseudomorphic serpentine mesh texture formed at the expense of olivine from assemblage 5. *B*, Antigorite blades (light gray) radiating from a serpentine mesh core (medium gray) with some magnetite rims (black).

apparently fairly homogeneous in the ultramafic rocks throughout the area.

## Oxides

Magnetite is a secondary mineral in the Red Lodge rocks and was formed during both of the serpentinization

events. It has five modes of occurrence: (1) It is most abundant as veins, dusty stringers, irregular clumps, and angular grains in serpentinized samples; (2) thick veins at hornblende rims and cleavages in a few grains in assemblage 1; (3) thin ragged rims on some chromite, and veins in chromite; (4) along phlogopite cleavage planes; and (5) anhedral grains in some samples of assemblage 1, and, in a few places, concentrated at triple-grain junctions of silicates. All these occurrences indicate that the magnetite is a late-stage mineral. It commonly contains exsolved needles of hematite, which indicates late-stage oxidizing conditions.

Chromite is present in amounts that range from less than 1 percent to 83 percent. In the following discussion, chromite that composes 25 percent or less of a sample is considered accessory and that which composes more than 25 percent is considered segregated. This terminology is modified from Thayer (1970).

Twenty-seven samples contain segregated chromite. It was found in all the assemblages except number 3, in which the maximum amount of chromite is 23 percent.

Segregated chromite is rarely euhedral, commonly subhedral to anhedral, and many grains have ragged boundaries. Most samples contain grains of highly cracked chromite, and many contain granulated zones and grains that have pull-apart fractures filled with serpentine or magnetite. The grains are typically 0.1–0.5 mm in diameter, and rarely as much as 1 mm. They are optically homogeneous and many appear to be unaltered, although the chemical compositions of some are clearly metamorphic as described below. A few grains have magnetite veins and rims, and some contain minute silicate inclusions. Relict igneous textures include chromite chains and occluded silicates.

The textures vary between segregated chromite samples. Many have the texture that James (1946) described as “closely spaced but not tightly packed grains” (fig. 5). Some samples, however, have areas as much as 1 cm across that consist of welded clumps of 100 percent chromite, a texture that required overgrowth for its formation.

Recrystallization of chromite is present locally; within the same ultramafic lens at North Star, one sample shows recrystallization along shears (fig. 6), whereas others show only angular splintering of chromite grains along shears, and still others show very little deformation.

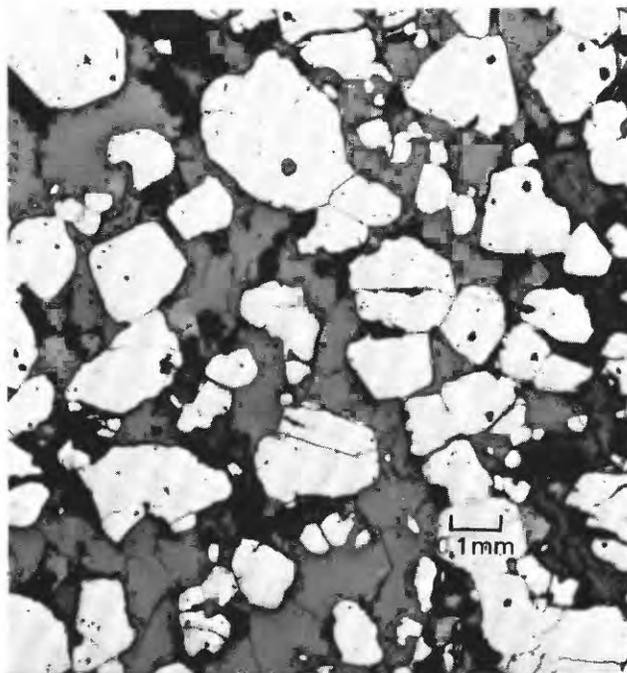
Like the segregated chromite, the accessory chromite grains are generally 0.1–0.5 mm in longest dimension, and rarely as much as 2 mm. The grains range in shape from euhedral to anhedral, and some occur as small welded clumps, a texture most commonly seen in the serpentinites. Serpentinized samples from assemblages 1 and 5 contain some grains that are anhedral, embayed by magnetite rims and veins, and have ragged grain boundaries (fig. 7). In contrast, chromite in samples showing little or no serpentinization, such as those in assemblage 3, lack magnetite rims and veins, although some chromite has ragged grain

boundaries and is flecked with tiny silicate inclusions (fig. 8).

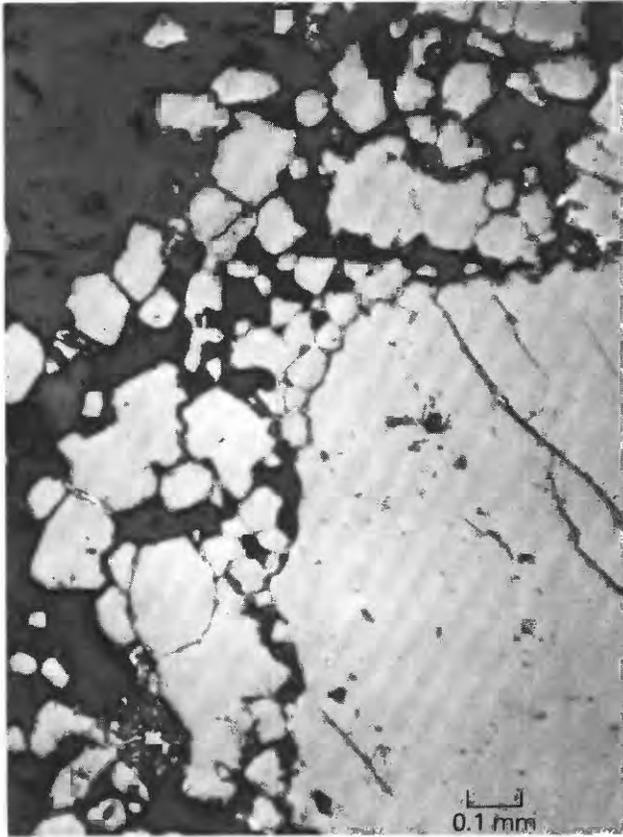
Most assemblage 1 samples contain two Cr-spinels: Al rich and Fe rich. The green metamorphic Al-rich chromite contains minute exsolved blebs of Fe-rich(?) chromite, which in turn contain lamellae of Al-rich(?) chromite. This exsolution feature as well as others observed in the Red Lodge chromites confirm the existence of an extensive solvus in the spinel compositional prism between Al- and Fe-rich chromite (Loferski, 1980; Loferski and Lipin, 1983). Exsolved chromites, of various textures, were found in all assemblages except the five blackwall samples of assemblage 6.

Most accessory chromite grains from Red Lodge are optically homogeneous and do not show the extensive zoning found in metamorphosed chromite from other locations. Magnetite veins and rims of various thicknesses are seen in some grains, particularly those in serpentinized areas, and thin oxidized zones are found along rims and cracks in some chromites.

Ferritchromit-chlorite intergrowths occur as alteration products of accessory chromite from other locations (see for example, Pinsent and Hirst, 1977; Lipin, 1980). Such intergrowths are found in a few of the Red Lodge chromites in assemblage 5 serpentinites, and in assemblage 1 Al-rich chromite where it is in contact with serpentinized zones. Such grains are altered to very fine grained crystallographi-



**Figure 5.** Photomicrograph taken in reflected light of segregated chromite (white) from assemblage 2, showing subhedral to anhedral shapes. The interstitial silicates are hornblende, minor chlorite, and talc.



**Figure 6.** Photomicrograph taken in reflected light showing recrystallized chromite from the North Star open pit. The silicate matrix is serpentine.

cally controlled intergrowths of the ferritchromite+chlorite(?) (fig. 9). In their study, Pinsent and Hirst (1977) also found preferential alteration of Al-rich relative to Fe-rich chromite. The association in the Red Lodge rocks of the ferritchromite+chlorite(?) alteration with serpentinized zones indicates that it is a late-stage alteration, formed during the last serpentinization, and is not a product of the high-grade metamorphism.

### Sulfides

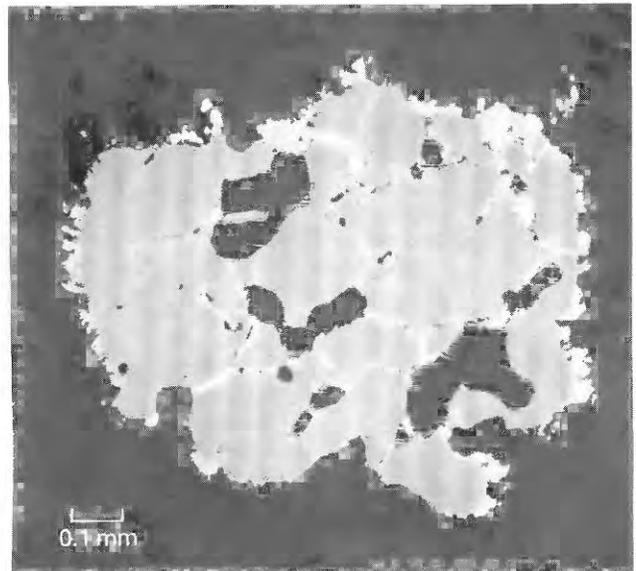
Sulfide minerals, mostly pyrite, chalcopyrite, and pentlandite, are present in trace amounts in most samples. They occur as minute inclusions in chromite, and as small masses with magnetite veins and rims in some serpentinites.

## MINERAL CHEMISTRY

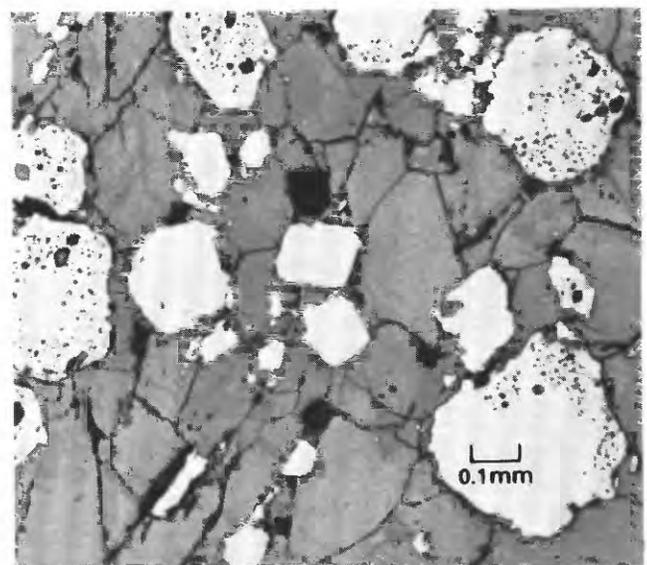
### Olivine

Table 3 shows microprobe analyses of olivine in two assemblage 5 samples from the North Star and Four

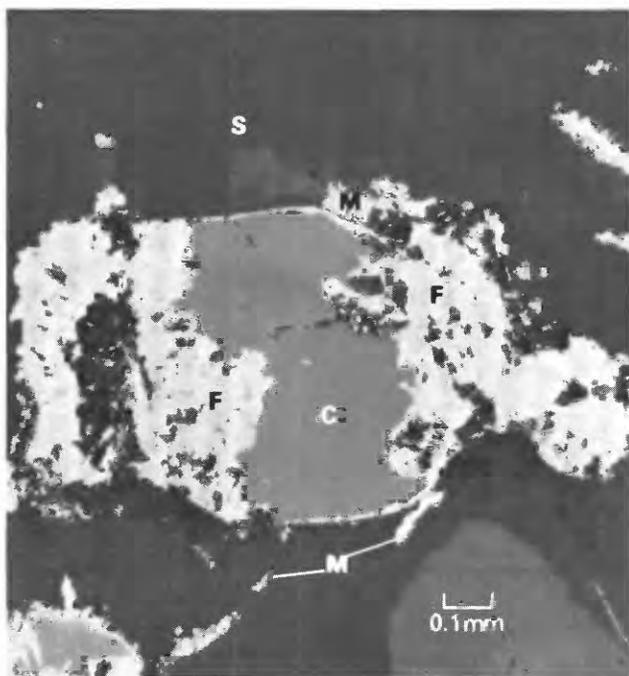
Chromes claims, in which olivine constitutes about 15 percent of each sample. Individual grains are homogeneous, and there is little variation between grains. The compositions are  $Fe_{92}$  in the sample from North Star and  $Fe_{90}$  in that from the Four Chromes deposit. The sample from Four Chromes contains 0.24 percent MnO and 0.14 percent NiO. The sample from North Star contains 0.35 percent NiO.



**Figure 7.** Photomicrograph taken in reflected light showing ragged accessory chromite from assemblage 5. The white is magnetite.



**Figure 8.** Photomicrograph taken in reflected light showing embayed chromite from assemblage 3 that contains tiny silicate inclusions, but no magnetite rims or veins.



**Figure 9.** Photomicrograph taken in reflected light of ferritchromit+chlorite(?) alteration along the grain boundaries of Al-rich chromite from assemblage 1. C indicates chromite; F, ferritchromit+chlorite; M, magnetite; and S, serpentine.

### Orthopyroxene

Microprobe analyses of orthopyroxene from two of the samples from the Highline deposit are given in table 3 and are plotted in the pyroxene quadrilateral (fig. 10). The orthopyroxenes have compositions of  $En_{86}$  and  $En_{91}$ . Calcium contents are low (a maximum of 0.19 percent CaO), and aluminum contents are moderate (a maximum of 2.21 percent  $Al_2O_3$ ). The low CaO contents indicate a metamorphic origin (Springer, 1974).  $Cr_2O_3$  is less than 0.07 percent, and 0.10 percent NiO was found in one sample.

### Clinopyroxene

Clinopyroxene was found at the Drill, Gallon Jug 2, Shovel, and Highline deposits. Microprobe analyses of three samples, one of which contains both orthopyroxene and clinopyroxene, are shown in table 3, and compositions of four samples are plotted in the pyroxene quadrilateral shown in figure 10.

Compositionally, three of the clinopyroxenes are augite, and one from the Highline deposit plots in the field of endiopside. Aluminum contents are less than 2 percent  $Al_2O_3$ , except for the sample of endiopside from the Highline deposit which contains about 6.5 percent  $Al_2O_3$ . The amount of  $Cr_2O_3$  is as high as 0.28 percent; NiO is less than

0.2 percent. Titanium was not detected in the augites; the endiopside contains 0.10 percent  $TiO_2$ .

### Amphibole

Magnesio-hornblende is the most common type of amphibole in the Red Lodge rocks according to Leake's (1978) amphibole classification scheme. Other types include tremolitic-, actinolitic-, edenitic-, ferro-edenitic-, and ferroan-pargasitic hornblende. Tremolite occurs in the ultramafic body at the Shovel claim. Microprobe analyses of amphiboles are presented in table 4. The method of Papike and others (1974) was used in calculating minimum and maximum values of  $Fe_2O_3$ , and cation proportions are given in terms of minimum  $Fe^{3+}$ .

Al/Si ratios in the amphiboles vary widely, both between samples and within some samples. The Edsel and Little Nell lenses contain amphiboles that are zoned from hornblende cores to tremolite or actinolite rims. The cores are slightly enriched in the minor elements Cr, Fe, Na, and K, relative to the rims.

The  $Al_2O_3$  in the hornblende ranges from 4.23 percent to 11.49 percent, and no correlation was found with the whole rock  $Al_2O_3$  content. Most hornblende contains about 12–13 percent CaO, up to 1.88 percent  $Na_2O$ , and 1.01 percent  $K_2O$ .  $Cr_2O_3$  is commonly less than 0.5 percent, but as much as nearly 3 percent occurs in amphiboles that are near chromite grains. A maximum of 0.25 percent NiO and 1.47 percent  $TiO_2$  were detected in the hornblende. Mg/(Mg+ $Fe^{2+}$ ) ratios of the hornblendes are typically greater than 0.85, but some are as low as 0.61.

Hornblende from the amphibolites at Highline and Gallon Jug 4 (table 4) have higher total FeO (fig. 11), and distinctly higher titanium contents than hornblende from associated ultramafic rocks. The two types of hornblende show no difference in chromium or nickel contents.

### Chlorite

Representative microprobe analyses of chlorites from three samples are shown in table 5. Most of the chlorites analyzed are clinocllore and penninite, according to Hey's (1954) classification, and one sample contained Fe-rich pyncochlorite. Ratios of Al/Si are variable in chlorites from samples with accessory chromite (see analyses LC-9(1) and LC-9(2) from table 5); whereas Al/Si is relatively constant in chlorites from samples with segregated chromite. The chlorites contain from 0.10 to 0.84 percent NiO.

$Cr_2O_3$  content is relatively low, from 0.58 to 1.10 percent in chlorite from samples containing accessory chromite, even where it is associated with ferritchromit

**Table 3.** Representative microprobe analyses of olivine, orthopyroxene, and clinopyroxene

[n.d., not determined]

Sample ----- Location ----- Assemblage -----	Olivine		Orthopyroxene		Clinopyroxene		
	HJ-2a-42 Four Chromes 5	HP-11 North Star 5	LC-11 Highline 5	LC-6 Highline 1	LC-1 Highline Amphibolite	LC-6 Highline 1	HP-2 Drill 3
<b>Weight Percent</b>							
SiO <sub>2</sub> -----	40.90	40.45	55.42	57.81	51.73	52.76	52.91
TiO <sub>2</sub> -----	.00	.00	.04	.00	.00	.10	.00
Al <sub>2</sub> O <sub>3</sub> -----	.00	.00	2.21	.71	1.22	6.56	1.21
Cr <sub>2</sub> O <sub>3</sub> -----	.00	.00	.07	.03	.01	.19	.28
FeO -----	9.57	8.26	10.21	6.50	9.72	4.53	6.24
MnO -----	.24	n.d.	.29	n.d.	n.d.	n.d.	n.d.
MgO -----	48.96	51.44	32.37	35.70	13.00	21.00	14.26
NiO -----	.14	.35	n.d.	.10	.07	.09	.13
CaO -----	n.d.	n.d.	.19	.04	22.80	12.71	24.27
Na <sub>2</sub> O -----	n.d.	n.d.	.00	.00	.38	.36	.38
Total	99.81	100.50	100.80	100.89	98.93	98.30	99.68
<b>Number of ions on the basis of 4 oxygens for olivine and 6 oxygens for pyroxene</b>							
Si -----	1.003	0.982	1.932	1.974	1.965	1.901	1.969
Al (IV) -----	.000	.000	.068	.026	.035	.099	.031
Al (VI) -----	.000	.000	.023	.003	.020	.181	.022
Ti -----	.000	.000	n.d.	n.d.	n.d.	n.d.	n.d.
Cr -----	.000	.000	.002	.001	.000	.006	.008
Fe -----	.196	.168	.297	.185	.309	.138	.194
Mg -----	1.791	1.861	1.682	1.818	.736	1.128	.791
Mn -----	.004	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni -----	.003	.007	n.d.	.002	.002	.003	.004
Ca -----	n.d.	n.d.	.007	.002	.928	.491	.968
Na -----	n.d.	n.d.	.000	.000	.029	.026	.028
Total	2.997	3.018	4.011	4.011	4.024	3.973	4.015
<b>Ratio</b>							
$\frac{\text{Mg}}{\text{Mg} + \text{Fe}^{2+}}$	0.90	0.92	0.89	0.91	0.70	0.89	0.80

grains. In segregated chromite however, the interstitial chlorite contains as much as 3.43 percent Cr<sub>2</sub>O<sub>3</sub>. Chromium values are variable within single grains, and show no regular pattern relative to the distance of the chlorite from a neighboring chromite grain.

The names *kämmererite* and *kotschubeite* have been used to describe Cr-rich chlorite where Cr<sup>3+</sup> is in octahedral and tetrahedral coordination respectively. Recent crystal structure refinements of Cr-chlorites, however, indicate that

Cr<sup>3+</sup> is not found in tetrahedral coordination, and is in fact in the interlayer octahedral sites of the chlorite structure (Phillips and others, 1980). Those authors suggested that the names *kämmererite* and *kotschubeite* be dropped and that Cr-rich chlorite should be named by adding the prefix "chromian" to the chlorite species. The Cr-rich chlorites of this study, therefore, are chromian-clinochlore, chromian-penninite, and chromian-pynochlorite, according to the classification of Hey (1954).

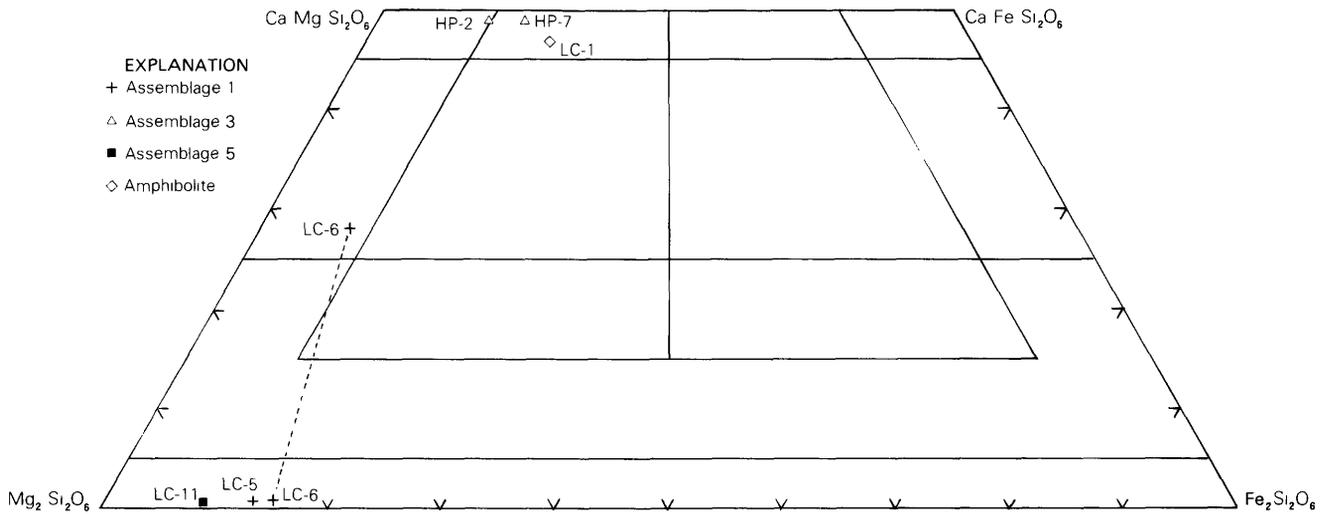


Figure 10. Compositional plot of pyroxene analyses on pyroxene quadrilateral.

### Phlogopite

Microprobe analyses of phlogopite from two samples are shown in table 5. One of the samples, LC-9, contains accessory chromite, the other contains segregated chromite. The phlogopite in the sample containing segregated chromite contains 1.20 percent  $\text{Cr}_2\text{O}_3$ , whereas that in the sample containing accessory chromite contains 0.49 percent  $\text{Cr}_2\text{O}_3$ .

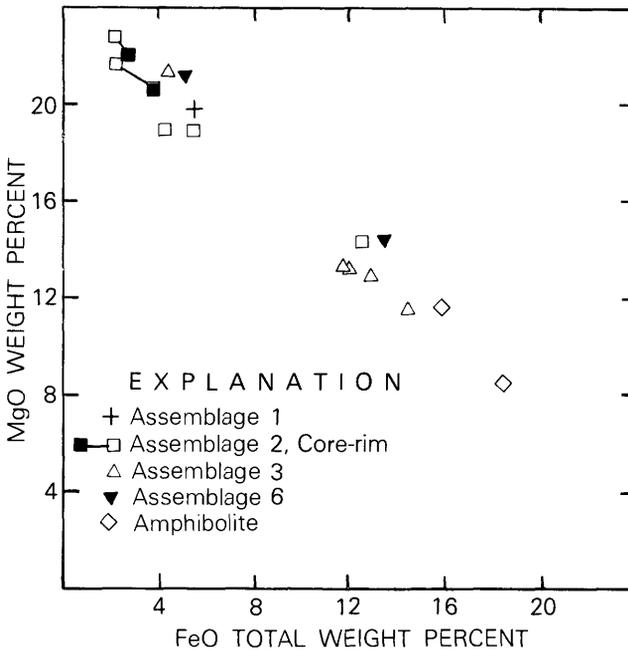


Figure 11. Compositional plot of weight percent FeO versus weight percent MgO in amphiboles from ultramafic rocks and from amphibolites. Tie lines connect cores and rims of amphibole grains.

### Serpentine

Serpentine minerals occur in all the ultramafic lenses, as alteration products of olivine, pyroxene, and amphibole minerals. Chemically, antigorite can be distinguished from lizardite and chrysotile by higher  $\text{SiO}_2$ , lower  $\text{H}_2\text{O}$ , and lower octahedral occupancies (Dungan, 1979). Microprobe analyses of serpentine minerals of various textures and signs of elongation ( $\alpha$  versus  $\gamma$ ) are given in table 6. Compositions are plotted with respect to  $\text{SiO}_2$ -MgO-FeO (fig. 12), and compositional fields of antigorite versus lizardite or chrysotile are shown (from Wicks, 1979).

The samples of  $\gamma$ -serpentine plot in or on the boundary of the antigorite field. Three analyses of mesh-textured  $\alpha$ -serpentine plot in the lizardite-chrysotile field, and two plot in the antigorite field. Pairs of analyses are given for three samples that contain areas of mesh-textured  $\alpha$ -serpentine and areas of nonpseudomorphic  $\gamma$ -serpentine. In all three samples, the nonpseudomorphic  $\gamma$ -serpentine is higher in  $\text{SiO}_2$  and plots within or on the boundary of the antigorite field, whereas the mesh-textured  $\alpha$ -serpentine is lower in  $\text{SiO}_2$ , and plots in or close to the lizardite-chrysotile field.

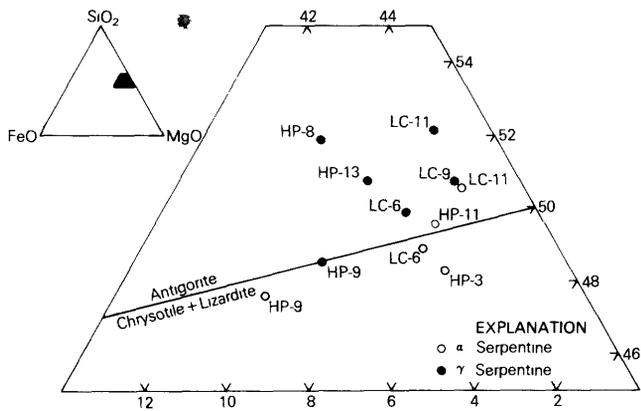
Therefore, on the basis of their chemistry and textures, the dominant serpentine minerals are lizardite and antigorite, and relative proportions between samples are variable.

### Chromite

Five samples of exsolved chromite are included in the following discussion of the compositions of the single-phase chromites. Those five samples contain minute intergrowths of host and guest phases, and the microprobe analyses represent bulk compositions for the grains. Detailed descrip-

**Table 4.** Representative microprobe analyses of amphibole

Sample -----	HP-2	HP-20B	HP-27	LC-8	HJ-4-42	HJ-4-42
Location -----	Drill	Gallon Jug 4	Shovel	Highline	Core	Rim
Assemblage -----	3	Amphibolite	3	6	Edsel	Edsel
					2	2
<b>Weight percent</b>						
SiO <sub>2</sub> -----	45.48	43.32	54.94	46.65	53.54	57.42
TiO <sub>2</sub> -----	.20	1.47	.00	.49	.07	.01
Al <sub>2</sub> O <sub>3</sub> -----	9.74	11.49	3.35	10.36	4.23	.45
Cr <sub>2</sub> O <sub>3</sub> -----	1.63	.05	.26	.08	1.13	.95
FeO -----	11.96	18.91	4.32	13.39	2.42	2.19
MgO -----	13.23	8.50	21.41	14.21	21.89	22.89
NiO -----	.25	.11	.14	.07	.11	.13
CaO -----	12.37	11.35	12.91	11.70	13.09	13.73
Na <sub>2</sub> O -----	1.17	1.42	.51	1.13	.89	.04
K <sub>2</sub> O -----	.97	.97	.20	.61	.33	.07
Total	97.00	97.59	98.04	98.69	97.70	97.88
<b>Number of ions on the basis of 23 oxygens for minimum Fe<sup>3+</sup></b>						
Si -----	6.663	6.552	7.577	6.706	7.385	7.879
Al (IV) -----	1.337	1.448	.423	1.294	.615	.073
Cr (IV) -----	.000	.000	.000	.000	.000	.048
Al (VI) -----	.407	.604	.133	.466	.100	.000
Ti -----	.022	.167	.000	.053	.007	.001
Cr -----	.220	.006	.031	.009	.156	.055
Fe <sup>3+</sup> -----	.152	.000	.086	.285	.048	.000
Fe <sup>2+</sup> -----	1.314	2.392	.413	3.051	.231	.251
Mg -----	2.913	1.927	4.413	.008	4.510	4.682
Ni -----	.030	.014	.016	1.325	.012	.014
Ca -----	1.942	1.840	1.908	1.802	1.935	2.018
Na (M4) -----	.000	.050	.000	.000	.000	.000
Na (A) -----	.332	.366	.136	.315	.238	.010
K -----	.181	.187	.035	.112	.058	.012
Total	15.513	15.553	15.171	15.426	15.295	15.043
<b>Ratio</b>						
Mg / (Mg + Fe <sup>2+</sup> )	0.69	0.45	0.91	0.70	0.95	0.95
<b>Calculated weight percent</b>						
Fe <sub>2</sub> O <sub>3</sub> Minimum	1.38	0.00	0.83	2.64	0.46	0.00
Maximum	3.23	3.42	3.97	9.10	2.69	.74
	Edenitic hornblende	Ferro- edenitic hornblende	Tremolite	Magnesian- hornblende	Tremolitic hornblende	Tremolite



**Figure 12.** Plot of serpentine compositions with respect to SiO<sub>2</sub>-MgO-FeO in weight percent. Compositional fields for antigorite, chrysotile, and lizardite are from Wicks (1979).

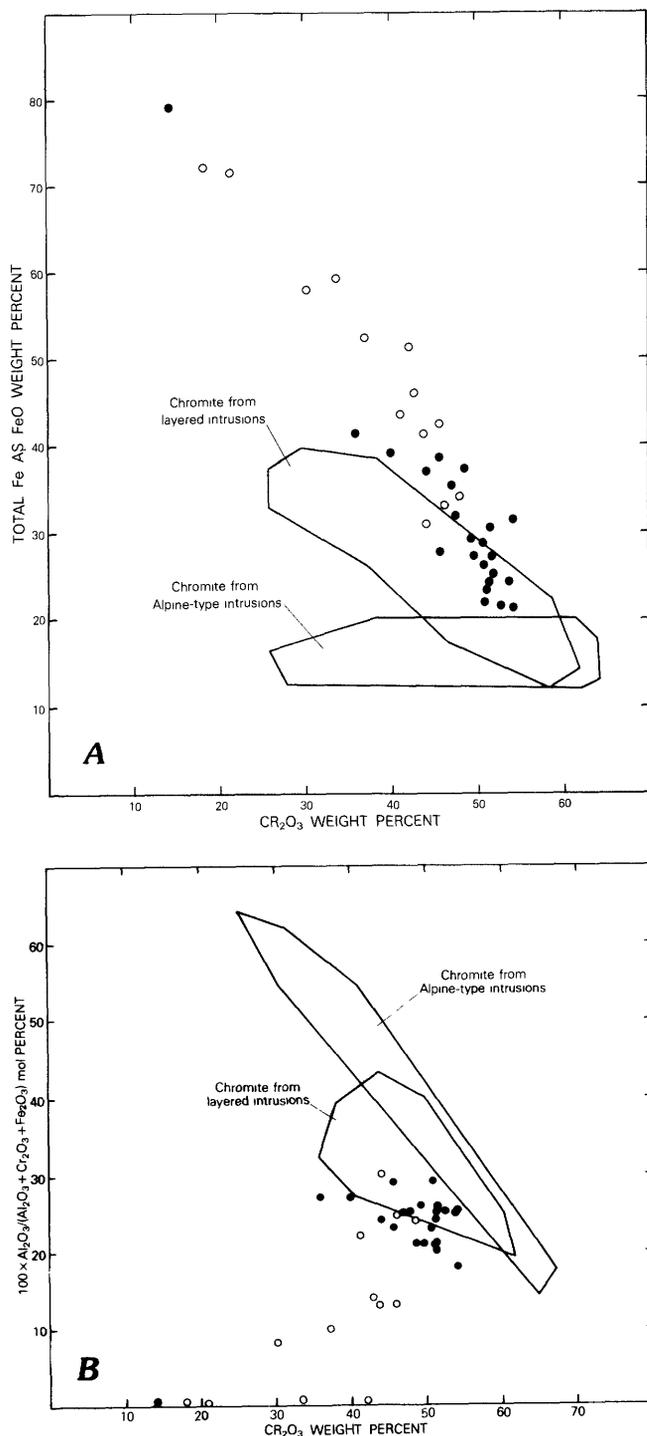
tions of those and other exsolved chromites from Red Lodge are given elsewhere (Loferski, 1980; Loferski and Lipin, 1983).

Microprobe analyses of segregated (table 7) and accessory chromite (table 8) indicate that the Cr<sub>2</sub>O<sub>3</sub> content ranges from about 14 percent to nearly 55 percent. The minor elements titanium and nickel are low in most of the chromite. Amounts of TiO<sub>2</sub> range from less than 0.1 percent up to 0.57 percent; most samples contain about 0.2 percent TiO<sub>2</sub>. These contents may be contrasted with chromite from the Stillwater Complex, which contains about 1 percent TiO<sub>2</sub>. Nickel contents range from less than 0.1 percent to 0.42 percent NiO; most samples contain 0.2–0.3 percent NiO, and these values are comparable to chromite from the Stillwater. No systematic variation exists between nickel and iron contents of the Red Lodge chromites.

The major-element composition of chromite may be used as a petrogenetic indicator (Thayer, 1970). The composition of much of the Red Lodge segregated chromite and nearly all the accessory chromite clearly has been modified. This is shown by a plot of the chromite compositions on Thayer-type (1970; modified by Thayer, 1980, oral commun.) variation diagrams on which compositional fields of primary magmatic chromite from stratiform and alpine-type deposits are outlined (fig. 13). Thayer's original stratiform field was distorted because Red Lodge and Fiskenaeset Complex (in west Greenland) metamorphosed samples were included. The field now consists of only primary magmatic chromite from the Stillwater Complex, the Bushveld Complex in South Africa, and the Great Dyke in Zimbabwe. The Red Lodge chromite that falls in a magmatic field has high-Fe stratiform-type rather than high-Al alpine-type compositions.

The general trend of chromite alteration is toward Fe-enrichment, and Al- and Mg-depletion (fig. 13), so that much of the Red Lodge chromite is actually homogeneous ferritchromite. Accessory chromite generally shows a greater

degree of alteration than the segregated chromite, as shown in figure 13, by greater departure from the magmatic



**Figure 13.** Compositions of segregated and accessory chromite. The fields of chromite from alpine-type and stratiform-type intrusions are from Thayer (1970), as modified by Thayer (oral commun., 1980). Open symbols, accessory chromite; closed symbols, segregated chromite. A, Cr<sub>2</sub>O<sub>3</sub> weight percent versus total Fe as FeO weight percent. B, Cr<sub>2</sub>O<sub>3</sub> weight percent versus Al<sub>2</sub>O<sub>3</sub>/(Al<sub>2</sub>O<sub>3</sub>+Cr<sub>2</sub>O<sub>3</sub>+Fe<sub>2</sub>O<sub>3</sub>) mol percent.

**Table 5.** Representative microprobe analyses of chlorite and phlogopite

[n.d., not determined]

Sample -----	Chlorite			Phlogopite	
	HJ-2a-42	LC-9(1)	LC-9(2)	HP-31	LC-9
Location -----	Four Chromes	Highline	Highline	North Star	Highline
Assemblage -----	5	5	5	4	5
<b>Weight percent</b>					
SiO <sub>2</sub> -----	30.55	29.23	35.64	40.27	38.13
TiO <sub>2</sub> -----	n.d.	.00	.00	.43	.66
Al <sub>2</sub> O <sub>3</sub> -----	19.58	19.79	11.75	14.52	15.84
Cr <sub>2</sub> O <sub>3</sub> -----	1.10	.86	.58	1.20	.49
FeO -----	3.17	3.18	2.05	1.24	3.06
MgO -----	31.25	32.00	35.79	27.09	27.29
NiO -----	.10	.22	.14	.35	.21
CaO -----	n.d.	.00	.00	.00	.00
Na <sub>2</sub> O -----	n.d.	.00	.00	.04	.05
K <sub>2</sub> O -----	n.d.	.00	.00	8.02	6.42
Total	85.75	85.28	85.95	93.16	92.15
<b>Number of ions based on 28 oxygens (chlorite) and 22 oxygens (phlogopite)</b>					
Si -----	5.847	5.642	6.747	5.711	5.469
Al (IV) -----	2.153	2.358	1.253	2.289	2.531
Al (VI) -----	2.263	2.150	1.369	.138	.148
Ti -----	n.d.	.000	.000	.046	.070
Cr -----	.169	.130	.086	.134	.056
Fe -----	.506	.511	.325	.147	.367
Mg -----	8.912	9.212	10.098	5.726	5.834
Ni -----	.011	.035	.033	.040	.023
Ca -----	n.d.	.000	.000	.000	.000
Na -----	n.d.	.000	.000	.012	.013
K -----	n.d.	.000	.000	1.451	1.175
Total	19.861	20.038	19.911	15.694	15.686
<b>Ratio</b>					
$\frac{\text{Mg}}{\text{Mg} + \text{Fe}^{2+}}$	0.95	0.95	0.97	0.98	0.94

chromite compositional field. This is to be expected because of the larger amount of silicates available for reaction with the accessory chromite.

#### Segregated Chromite

Segregated chromite shows no significant grain-to-grain chemical variation within individual samples, and sin-

gle grains show virtually no zoning. Compositions of segregated chromite are plotted in figure 14, which also shows the compositional fields for chromite from alpine and stratiform complexes in general and for the Stillwater complex in particular. The Stillwater field is included to show a typical compositional range of chromite from a single stratiform complex.

Figure 14 shows that the Red Lodge segregated chromite is more similar to stratiform- than to alpine-type

**Table 6.** Representative microprobe analyses of serpentinite

[n.d., not determined]

Sample -----	HP-3( $\alpha$ )	HP-13( $\gamma$ )	LC-11( $\alpha$ )	LC-11( $\gamma$ )	LC-6( $\alpha$ )	LC-6( $\gamma$ )
Location -----	Drill	North Star	Highline	Highline	Highline	Highline
Assemblage -----	3	5	5	5	1	1
SiO <sub>2</sub> -----	40.79	43.44	43.01	44.62	41.09	42.39
TiO <sub>2</sub> -----	.10	.00	.00	.00	.00	.00
Al <sub>2</sub> O <sub>3</sub> -----	1.86	.28	.60	.24	1.74	1.66
Cr <sub>2</sub> O <sub>3</sub> -----	.18	.03	.00	.00	.00	.00
FeO -----	4.51	3.19	1.33	1.17	2.76	2.73
MgO -----	39.49	39.09	40.76	39.83	40.10	39.80
NiO -----	<u>n.d.</u>	<u>.19</u>	<u>.08</u>	<u>.04</u>	<u>.12</u>	<u>.07</u>
Total	86.93	86.22	85.78	85.90	85.81	86.65
<b>Number of ions on the basis of 14 oxygens</b>						
Si -----	3.857	4.096	4.041	4.163	3.903	3.973
Al (IV) -----	.143	.031	.000	.000	.097	.027
Al (VI) -----	.065	.000	.066	.026	.097	.155
Cr -----	.000	.003	.000	.000	.000	.000
Fe -----	.355	.252	.105	.091	.221	.214
Mg -----	5.567	5.493	5.707	5.540	5.678	5.558
Ni -----	<u>n.d.</u>	<u>0.014</u>	<u>.006</u>	<u>.003</u>	<u>.011</u>	<u>.007</u>
Total	9.987	9.889	9.952	9.823	10.007	9.934
<b>Ratio</b>						
$\frac{\text{Mg}}{\text{Mg} + \text{Fe}^{2+}}$	0.94	0.96	0.98	0.98	0.96	0.96

chromite. The Red Lodge chromite shows a broader compositional range than unmetamorphosed chromite from a single stratiform complex, such as the Stillwater, as a result of Fe-enrichment during metamorphic alteration.

Most of the segregated chromite occurs in the amphibole-rich rocks of assemblage 2 and in the serpentinites of assemblage 5. The chromite from assemblage 2 shows slightly lower Mg/(Mg+Fe<sup>2+</sup>) ratios, higher Cr/(Cr+Al) ratios, lower Fe<sup>3+</sup>/R<sup>3+</sup> ratios, and a somewhat broader compositional range (fig. 14).

Distinct, although overlapping, compositional fields again appear where the segregated chromite is grouped according to the deposit in which it occurs (fig. 15). The chromite compositions, even though they are now altered, seem to reflect some primary compositional differences between the deposits that cannot be attributed to different host rock mineralogy. The most marked compositional difference is in the Mg/(Mg+Fe<sup>2+</sup>) ratio. Segregated chromite

from the Little Nell deposit is the lowest in Mg/(Mg+Fe<sup>2+</sup>) and is actually ferritchromite (table 7). Segregated chromite from the Highline and North Star deposits has the highest Mg/(Mg+Fe<sup>2+</sup>) ratios.

#### Accessory Chromite

Most of the accessory chromite grains are essentially homogeneous ferritchromite, and a few have patches of even greater iron enrichment at the grain boundaries. Two compositional groups are present in a sample of exsolved chromite from the North Star deposit (table 8, sample HP-9). Other samples show little or no grain-to-grain variation.

The compositions of the accessory chromite according to assemblages are shown in figure 16. Most samples are in assemblages 3 and 5, and, like the segregated chromite, those from the amphibole-rich rocks of assemblage 3 are

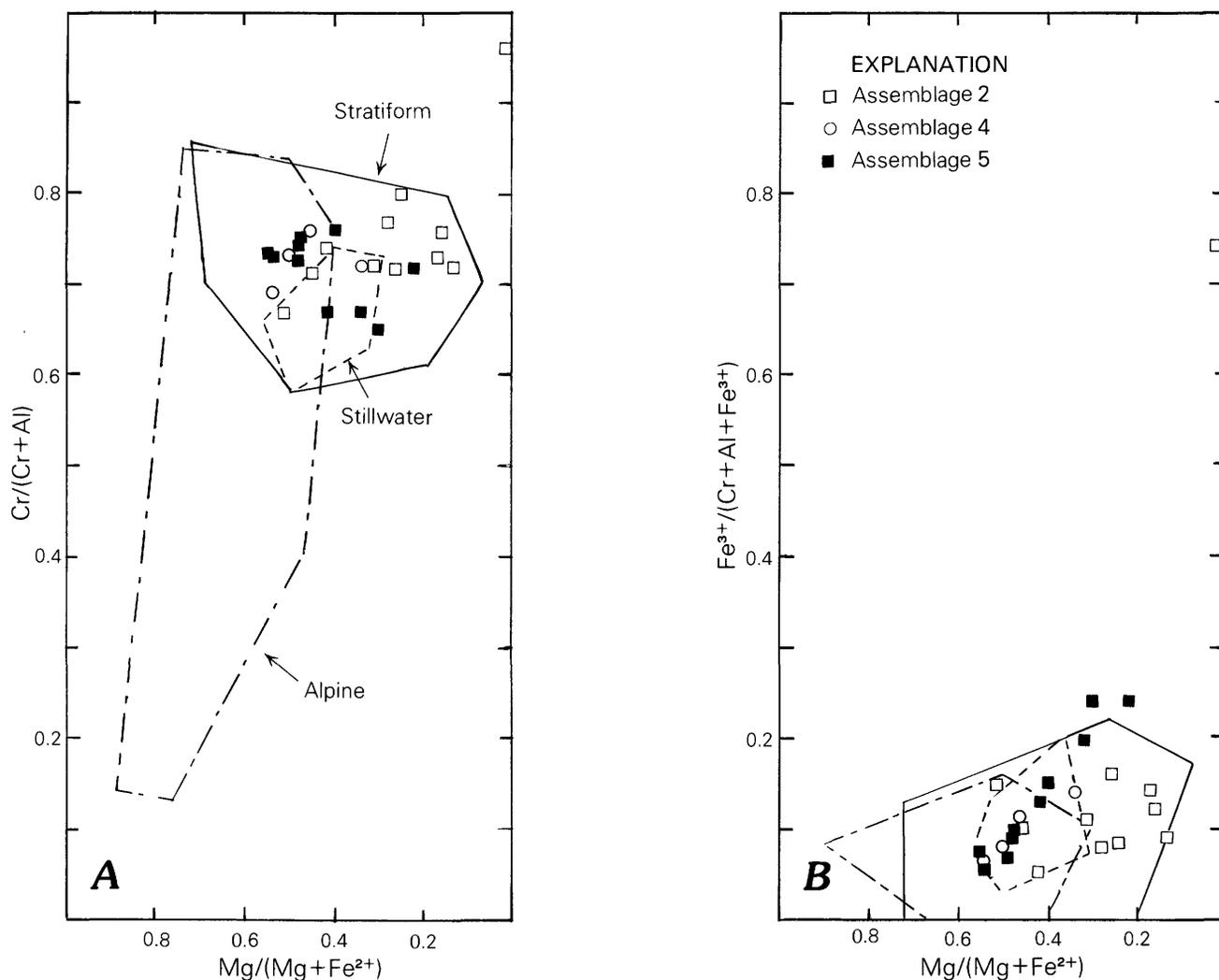
slightly lower in  $Mg/(Mg+Fe^{2+})$  than those from the serpentinites of assemblage 5.

The chromite from the Red Lodge assemblage 5 serpentinites does not fall into the general compositional field of chromite from serpentinites as determined by Evans and Frost (1975) (fig. 16). Those authors showed that accessory Cr-spinels from alpine-type serpentinites are extremely iron rich and become progressively enriched in Cr, Mg, and Al as metamorphism increased. The Red Lodge assemblage 5 samples overlap the higher grade chromite compositional fields shown by those authors. This evidence, along with the serpentine mineralogy and textures, indicates that the Red Lodge serpentinites are retrograde in origin. The chromite compositions were established at higher metamorphic grade, and were preserved during the retrograde serpentinization, and the subsequent slight prograde event.

The samples from the highest grade orthopyroxene-bearing rocks of assemblage 1 all contain green Al-rich and opaque Fe-rich chromite as exsolved grains. The formation of the metamorphic green spinel indicates a trend toward Al- and Mg-enrichment at high metamorphic grades. This finding concurs with that of Evans and Frost (1975).

The ferritchromite from the Red Lodge samples, including homogeneous grains and intergrowths with chlorite, contains more  $Al_2O_3$  than  $MgO$ , which is the reverse of ferritchromite compositions reported from most other locations (table 9). The silicate assemblages in many of the Red Lodge samples are also high in  $Al_2O_3$  as shown by bulk-rock chemical analyses. Thus, the bulk-rock chemistry apparently controls the ferritchromite compositions.

Not all ferritchromite in the Red Lodge samples is associated with chlorite. Other workers have found ferritchromite without chlorite rims or intergrowths (Ulmer,



**Figure 14.** Compositions of segregated chromite from the various assemblages. The fields of chromite from alpine- and stratiform-type intrusions and from the Stillwater Complex are from Irvine (1967). A,  $Mg/(Mg+Fe^{2+})$  versus  $Cr/(Cr+Al)$  mol percent. B,  $Mg/(Mg+Fe^{2+})$  versus  $Fe^{3+}/(Cr+Al+Fe^{3+})$  mol percent.

**Table 7.** Representative microprobe analyses of segregated chromite

[n.d., Not determined; calc., calculated]

Location --	North Star			Gallon Jug 2	Gallon Jug 4		Pick		Shovel	
Sample ----	HJ-24-42	HP-31	HP-10A	HJ-73-42	HJ-26-42	HP-22	HP-30	HJ-68-42	HJ-32-42	HJ-15-42
Assemblage -	5	4	5	2	3	4	5	2	2	2
<b>Weight percent</b>										
TiO <sub>2</sub> -----	0.24	0.20	0.14	0.20	0.20	0.37	0.17	0.32	0.28	0.27
Al <sub>2</sub> O <sub>3</sub> -----	12.83	13.08	10.28	13.55	12.32	11.80	11.36	11.77	12.46	11.19
Cr <sub>2</sub> O <sub>3</sub> -----	52.64	51.58	50.14	49.06	51.98	46.21	50.96	44.18	47.57	45.79
FeO -----	21.71	24.44	28.70	27.23	25.28	33.32	26.42	37.25	31.97	38.90
MgO -----	11.23	10.32	8.64	9.23	9.91	6.67	9.57	5.06	6.16	3.35
NiO -----	n.d.	.28	.42	.15	n.d.	.28	.25	n.d.	.15	n.d.
Total	98.65	99.90	98.32	99.42	99.69	98.65	98.73	98.58	98.59	99.50
Fe <sub>2</sub> O <sub>3</sub> calc.	5.49	6.79	9.86	8.28	6.94	10.85	8.37	12.23	8.35	10.99
FeO calc.	16.77	18.33	19.83	19.78	19.03	23.56	18.89	26.25	24.45	29.01
New total	99.20	100.58	99.31	100.25	100.38	99.74	99.57	99.81	99.43	100.60
<b>Formula proportions: cation sum = 3</b>										
Al -----	0.494	0.500	0.408	0.521	0.474	0.470	0.445	0.471	0.498	0.454
Cr -----	1.360	1.324	1.336	1.265	1.346	1.235	1.337	1.197	1.276	1.248
Fe <sup>3+</sup> -----	.135	.166	.250	.203	.171	.276	.209	.316	.213	.285
Ti -----	.006	.005	.003	.005	.005	.010	.004	.008	.007	.007
Fe <sup>2+</sup> -----	.458	.498	.559	.539	.521	.666	.524	.754	.693	.836
Mg -----	.547	.500	.433	.448	.483	.336	.473	.258	.310	.170
Ni -----	n.d.	.007	.011	.019	n.d.	.007	.008	n.d.	.003	n.d.

1974; Bliss and MacLean, 1975; Hoffman and Walker, 1978). In this mode of occurrence, ferritchromit may be formed by the reaction of chromite with magnetite rims during metamorphism of a lizardite+magnetite+chromite assemblage to form antigorite+chromite+ferritchromit+magnetite (Bliss and MacLean, 1975).

The compositions of the single-phase chromite, both accessory and segregated, are shown with respect to Cr-Al-Fe<sup>3+</sup> and the projected solvus defined by the exsolved chromite (fig. 17). The solvus extends from the Fe<sup>3+</sup>-Al join to more Cr-rich compositions than have previously been reported in exsolved chromite from other rocks (see Muir and Naldrett, 1973). The top of the solvus is where Cr/(Cr+Al+Fe<sup>3+</sup>) = 0.61. The single-phase Red Lodge chromites generally plot toward the Cr end of the Cr-Al join in figure 17, and a few plot near the Fe<sup>3+</sup> end of the Cr-Fe<sup>3+</sup> join. None of the single-phase chromites plot within the two-phase field defined by the solvus.

## CONTACT METAMORPHISM

Table 10 shows bulk rock analyses of samples taken at distances ranging from 10 cm to 45 m from the monzonite dike at the Highline claim. The most pronounced differences are in CaO content, which is much greater near the dikes, and in MgO content, which is much less near the dike. SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, and MnO contents all are greater near the dike. Samples LC-6, 9, and 10 probably reflect primary compositional ranges.

Abundant hornblende, with or without feldspar, biotite, and zoisite, was found in samples taken about 5-10 cm from the dike. Abundant hornblende and talc as well as exsolved chromite were found in the samples taken about 0.5 m from the dike. Assemblage 1 was found at distances of 3-10 m and throughout the Highline ultramafic body, which indicates that those high-grade rocks were probably formed by the regional rather than the contact

**Table 7.** Representative microprobe analyses of segregated chromite—Continued

[n.d., Not determined; calc., calculated]

Four Chromes		Little Nell				Edsel			Highline		
HJ-33-42	HJ-34a-42	HJ-87-42	HJ-84-42	HJ-80-42	HJ-10-42	HJ-4-42	HJ-9-42	HJ-70-42	HJ-69-42	LC-13	LC-15
2	5	2	2	2	2	2	2	5	5	4	2
<b>Weight percent—Continued</b>											
0.44	0.57	0.27	0.13	0.02	0.22	0.27	0.16	0.23	0.20	0.12	0.25
13.41	13.30	12.20	10.13	.42	12.58	10.50	8.97	13.19	10.68	15.59	15.23
39.90	36.09	47.02	48.78	14.32	53.89	51.61	54.12	53.79	51.60	50.77	45.73
39.27	41.65	35.76	37.31	79.24	24.56	30.59	31.93	21.84	27.27	22.27	27.90
6.49	6.09	2.50	3.21	.04	8.59	5.47	4.91	11.23	9.39	11.28	9.45
n.d.	.20	n.d.	n.d.	.30	n.d.	n.d.	n.d.	n.d.	.08	.23	.30
99.51	97.90	97.75	99.56	94.34	99.84	98.44	100.09	100.28	99.22	100.26	98.86
16.10	18.73	6.62	9.35	53.73	3.82	6.17	6.31	5.04	8.81	5.47	13.16
24.78	24.80	29.81	28.90	30.90	21.12	25.03	26.25	17.31	19.34	17.35	16.06
101.12	99.78	98.42	100.50	99.73	100.22	99.05	100.72	100.79	100.10	100.81	100.18
<b>Formula proportions: cation sum = 3—Continued</b>											
0.526	0.529	0.506	0.413	0.023	0.489	0.427	0.363	0.500	0.417	0.585	0.586
1.049	.966	1.307	1.337	.535	1.406	1.405	1.457	1.369	1.355	1.278	1.179
.403	.477	.175	.244	1.549	.095	.160	.163	.122	.220	.131	.323
.011	.014	.006	.003	.000	.005	.007	.003	.004	.004	.003	.006
.689	.702	.876	.838	.990	.583	.721	.753	.466	.537	.462	.438
.322	.307	.130	.165	.001	.422	.280	.251	.539	.465	.535	.460
n.d.	.005	n.d.	n.d.	.009	n.d.	n.d.	n.d.	n.d.	.002	.006	.008

metamorphism. Contact metamorphic effects, therefore, extend to a distance from 0.5 m and 3 m from the dike.

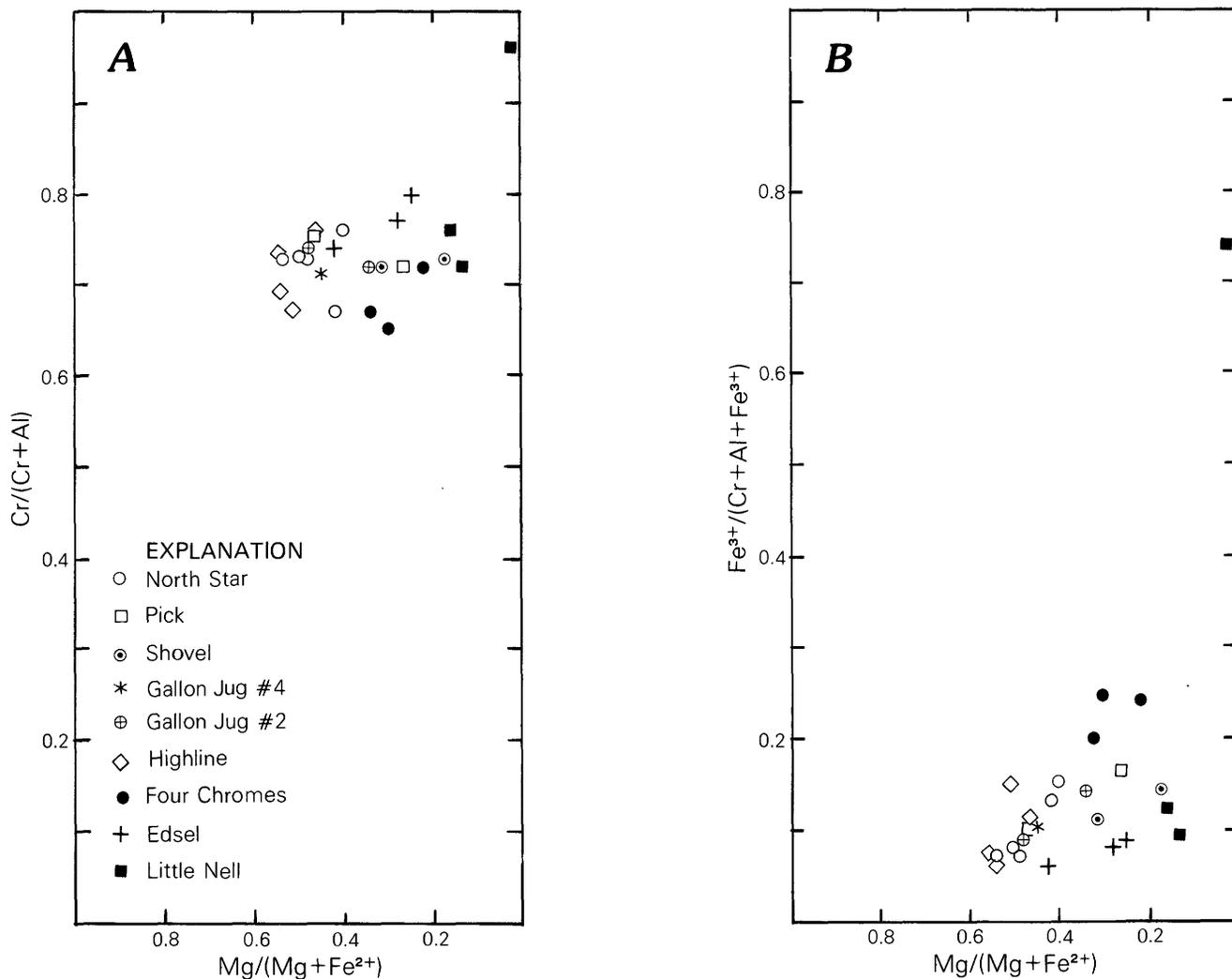
The bulk composition of the chromite was indirectly affected by the metasomatism. Chromite taken 0.5 m from the dike contains about 10 percent  $Al_2O_3$ , whereas that taken farther from the dike contains about 30–60 percent. The high Ca content near the dike produced the Ca-Al silicates, whereas farther from the dike, where the Ca content was low, the chromite was enriched in the available Al.

## GEOCHEMISTRY

Table 11 shows representative major oxide analyses and C.I.P.W. norms of ultramafic samples from the various assemblages and of amphibolites from the contacts with some of the ultramafic lenses. Average values for ultramafic rocks and for continental tholeiitic basalt are included for comparison.

The Red Lodge ultramafic rocks show a wide range in chemical composition. Silica variation diagrams for the major oxides (fig. 18) show that  $SiO_2$  values range from about 36 percent to more than 52 percent. The other major oxides, MgO, FeO, CaO, and  $Al_2O_3$ , also have values that range between the averages of ultramafic and mafic rocks (fig. 18). The plots show smooth continuous trends, and samples from each assemblage generally fall in distinct fields of the diagrams. The minor oxides,  $TiO_2$  and  $Na_2O$ , are low in the Red Lodge ultramafics and are closer to the values of an ultramafic than to those of a mafic rock (fig. 18).

Analyses of the trace elements, Cr, Ni, Co, and Sc, and average values for ultramafic and mafic rocks are shown in table 12. Most trace-element contents are similar to values from other ultramafic rocks (Himmelberg and Coleman, 1968; Muir, 1979; Stosch and Seck, 1980), unlike the major oxides, which show wide variations from ultramafic to mafic compositions. Only Sc shows a difference among the



**Figure 15.** Compositions of segregated chromite from the various deposits. *A*, Mg/(Mg+Fe<sup>2+</sup>) versus Cr/(Cr+Al) mol percent. *B*, Mg/(Mg+Fe<sup>2+</sup>) versus Fe<sup>3+</sup>/(Cr+Al+Fe<sup>3+</sup>) mol percent.

assemblages, and shows low contents in the serpentinites of assemblage 5 that correspond to the average of 5 ppm Sc in dunites (Goles, 1967). Most of the other rocks are between that value and the average for pyroxenites of 40 ppm Sc, so many of the Red Lodge rocks may have originally been peridotites.

Pt, Pd, and Rh contents of 14 of the Red Lodge samples, including 5 segregated chromites, are shown in table 12. Segregated chromite contains significantly more Rh and typically less Pd than accessory chromite, whereas Pt contents are variable. High Rh contents have been found in segregated chromite from other areas (Page and others, 1979). The Pt, Pd, and Rh contents of segregated chromite from the unmetamorphosed Stillwater Complex (Page and others, 1969) are significantly higher than those from the Red Lodge Samples. In contrast, values from the Fiskenaasset Complex of Greenland (Page and others, 1980), an upper-amphibolite facies stratiform intrusion, are similar to those from Red Lodge, which may indicate

mobility of the platinum group metals during high-grade metamorphism. The various elemental ratios in the Red Lodge rocks are similar to the ratios in both the Stillwater and the Fiskenaasset.

The major oxide contents of the Red Lodge amphibolites associated with the ultramafic rocks are consistently close to the average composition of continental tholeiite (table 11 and fig. 19). Plots of amphibolite compositions (fig. 19) also indicate tholeiitic compositions. This conclusion agrees with that of other workers (Armbrustmacher and Simons, 1977; Simons and others, 1979).

The Red Lodge rocks, therefore, show a range in composition between mafic and ultramafic rocks, with some assemblages such as 1 and 7 closer to average ultramafic rocks, and other assemblages such as 3 and 4 closer to average mafic rocks in terms of the major oxides. A similar range in compositions was noted by Skinner (1969) in the

ultramafic rocks from the nearby Highline Trails Lakes area.

## PETROGENESIS

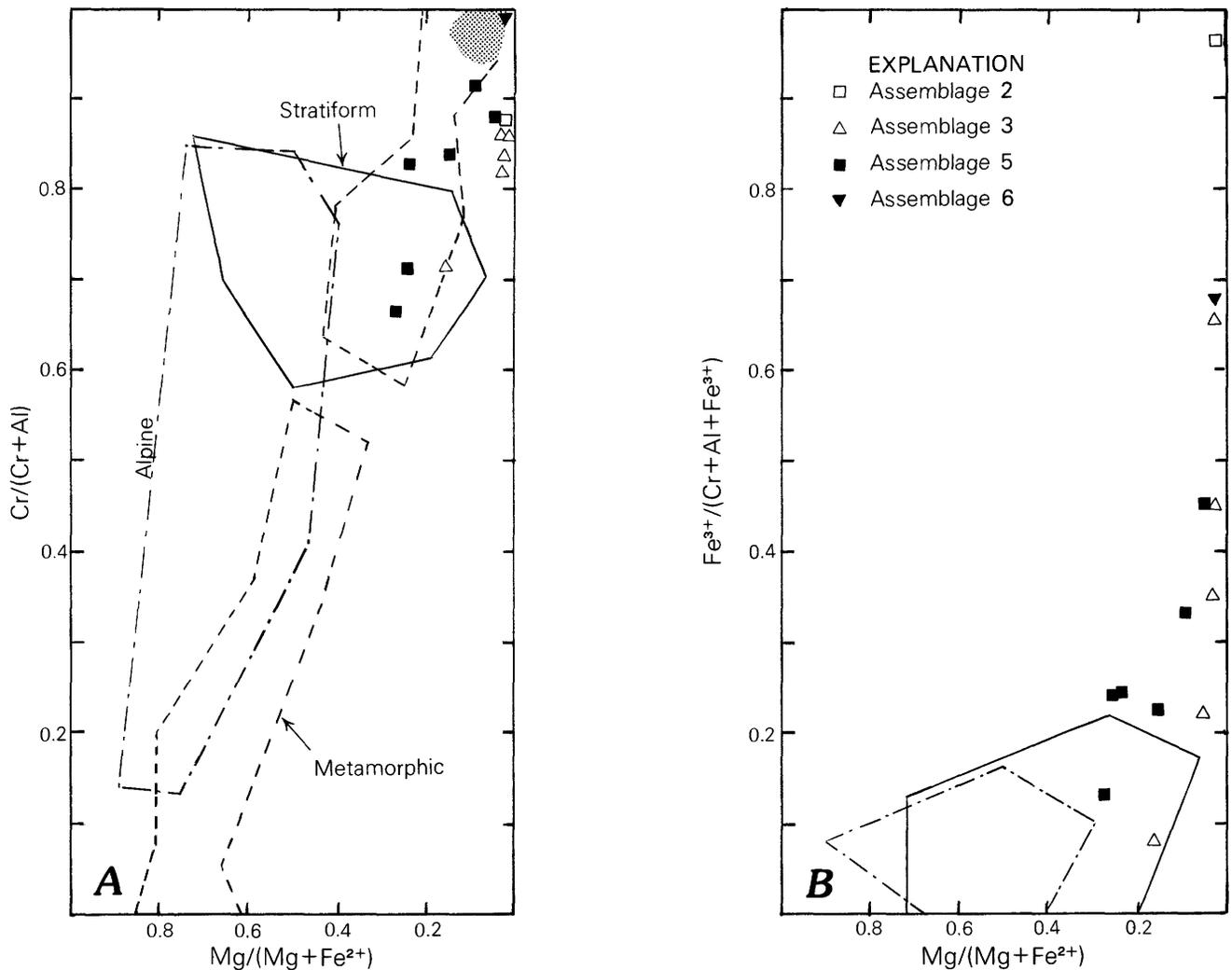
As stated previously, the origin of the Red Lodge ultramafic rocks is problematic because of the high-grade metamorphic overprint. The high CaO and Al<sub>2</sub>O<sub>3</sub> contents of many of the samples relative to average ultramafic rocks suggest two possibilities: (1) extensive metasomatism during the metamorphism of some rocks that were all originally ultramafic, or (2) essentially isochemical metamorphism of diverse rocks.

The first possibility would require the movement of large amounts of material. Although there is a source of

calcium and aluminum in the country rocks, the evidence against extensive metasomatism includes:

1. In general, blackwall zones, marked by the formation of Al-rich phases such as chlorite near the margins of ultramafic bodies, are formed by Mg migration out of the ultramafic rocks into the Al-rich country rocks. Aluminum does not migrate into ultramafic rocks (Chidester, 1962). Even at high metamorphic grade, blackwall zones are thin, usually less than 1 m wide, and do not extend to the interiors of ultramafic bodies.

2. As shown previously, metasomatic introduction of CaO, and to a minor extent Al<sub>2</sub>O<sub>3</sub>, occurs near the monzonite porphyry dike in the Highline open pit, but only in samples taken within 3 m of the dike. Thus, the calcium and aluminum did not migrate over long distances.



**Figure 16.** Compositions of accessory chromite. The fields of chromite from alpine- and stratiform-type intrusions are from Irvine (1967); the field of metamorphic accessory chromite including chromite from serpentinite (stippled field) is from Evans and Frost (1975). A, Mg/(Mg+Fe<sup>2+</sup>) versus Cr/(Cr+Al) mol percent. B, Mg/(Mg+Fe<sup>2+</sup>) versus Fe<sup>3+</sup>/(Cr+Al+Fe<sup>3+</sup>) mol percent.

**Table 8.** Representative microprobe analyses of accessory chromite

[calc., calculated]

Sample ----- Location ----- Assemblage -----	HP-2 Drill	HP-4A Drill	HP-10B North Star	HP-11 North Star	HP-13 North Star	HP-26 Shovel	SR-1 Four Chromes	HP-9 North Star	HP-9 North Star
	3	3	5	5	5	3	6	5	5
<b>Weight percent</b>									
TiO <sub>2</sub> -----	0.39	0.15	0.05	0.48	0.24	0.47	0.14	0.24	0.19
Al <sub>2</sub> O <sub>3</sub> -----	4.37	11.39	15.44	6.02	5.89	6.50	.15	2.85	2.94
Cr <sub>2</sub> O <sub>3</sub> -----	37.04	48.40	42.62	43.86	45.57	42.74	21.68	33.72	42.26
FeO -----	52.70	34.32	33.89	41.57	42.60	46.02	71.64	59.71	51.39
MgO -----	.14	3.23	5.62	4.64	2.70	.28	.22	.65	1.72
NiO -----	.34	.22	.11	.30	.24	.31	.29	.23	.12
Total	94.98	97.71	97.73	96.87	97.24	96.32	94.12	97.35	98.62
FeO (calc.)	31.52	28.25	25.29	25.39	27.98	31.92	30.49	31.24	29.94
Fe <sub>2</sub> O <sub>3</sub> (calc.)	<u>23.54</u>	<u>6.74</u>	<u>9.55</u>	<u>17.98</u>	<u>16.25</u>	<u>15.67</u>	<u>45.73</u>	<u>31.65</u>	<u>23.84</u>
New Total	97.34	98.38	98.68	98.67	98.87	97.89	98.70	100.53	101.01
<b>Formula proportions: cation sum = 3</b>									
Al -----	0.195	0.471	0.616	0.253	0.251	0.284	0.007	0.124	0.125
Cr -----	1.111	1.343	1.139	1.238	1.302	1.252	.660	.984	1.212
Fe <sup>3+</sup> -----	.672	.178	.243	.483	.442	.437	1.325	.879	.653
Ti -----	.011	.004	.001	.013	.007	.013	.004	.006	.005
Fe <sup>2+</sup> -----	1.000	.829	.715	.758	.846	.989	.982	.964	.908
Mg -----	.001	.169	.283	.247	.146	.015	.013	.036	.093
Ni -----	.010	.006	.003	.008	.006	.010	.009	.007	.004

3. If metasomatism were extensive, then all the ultramafic rocks probably would have been at least somewhat affected because the ultramafic rocks all occur in similar country rocks. However, there is no evidence of Ca and Al metasomatism in many of the rocks, such as the serpentinites.

The second possibility, favored here, explains the chemical diversity of the Red Lodge rocks by isochemical or nearly isochemical metamorphism of diverse original parent rock types. On the basis of the chemical and textural evidence, the original rocks included dunites (now assemblage 5 serpentinites), harzburgites (now rocks of assemblage 1), feldspar- or clinopyroxene-rich chromitites (now assemblage 2) and pyroxenites, or rocks approaching gabbroic compositions (now assemblage 3). The normative analyses (table 11), although by no means considered as conclusive proof, indicate mafic assemblages for some of the rocks, with as much as 36 percent feldspar. Thus, the abundant modal hornblende in the rocks was formed by

metamorphic reaction of original plagioclase with olivine and pyroxene.

The deformation and metamorphism have caused debate concerning whether the Red Lodge ultramafic rocks are alpine-type (James, 1946) or tectonically disrupted stratiform-type deposits, possibly fragments of the Stillwater Complex (Thayer, 1970; Bowes and Skinner, 1969). The characteristics of the two types of complexes have been described in the literature (Thayer, 1960, 1967, and 1970; Coleman, 1977; Girardi and Ulbrick, 1980), and the three possibilities are considered as follows:

1. Alpine type: James (1946) classified the Red Lodge ultramafics as alpine type because of their lenticular forms. However, rock types characteristically associated with alpine-type ophiolites (see Coleman, 1977) are lacking in the Red Lodge area, and the Archean Red Lodge rocks are much older than known ophiolites, which are all Phanerozoic in age. The Red Lodge chromite compositions do not correspond to those from

alpine-type deposits (compare fig. 13 and 14). In addition, characteristic textures in alpine-type chromitites, such as coarse grain size and chromite nodules (Thayer, 1960), are not present at Red Lodge. Thus, the Red Lodge deposits are probably not alpine type.

2. Fragments of the Stillwater Complex: This idea is attractive because of the proximity of the Red Lodge and Stillwater areas. However, the Stillwater Complex, except for some serpentinization, is unaltered, whereas the

Red Lodge ultramafic rocks were profoundly affected by the 2,800 m.y. metamorphic event. This makes any connection between the Red Lodge and Stillwater ultramafic rocks unlikely because the Red Lodge rocks appear to be older.

3. A third possibility is that the Red Lodge ultramafics were derived from a layered intrusion like the Stillwater which was tectonically disrupted. A similar origin was proposed for small ultramafic bodies in the

**Table 9.** Ferritchromit analyses from other locations

[n.d. = not determined]

	1.	2.	3.	4.	5.	6.	7.
TiO <sub>2</sub>	0.6	1.04	< 0.02	0.12	0.42	n.d.	0.31
Al <sub>2</sub> O <sub>3</sub>	1.0	3.1	.29	1.8	.06	0.3	.26
Cr <sub>2</sub> O <sub>3</sub>	13.9	42.0	38.8	56.0	14.87	37.8	28.10
Fe <sub>2</sub> O <sub>3</sub>	n.d.	22.4	30.4	13.1	55.05	n.d.	39.30
FeO	76.2	30.16	25.2	14.7	25.97	52.1	27.90
MgO	3.0	2.1	3.09	10.1	3.15	3.3	2.29
NiO	n.d.	n.d.	.43	.49	.47	n.d.	.39
MnO	.3	n.d.	.69	.47	n.d.	n.d.	.75
Total	95.0	100.80	98.92	96.78	99.99	93.5	99.3

1. Springer, 1974, analysis A41B, p. 177.
2. Beeson and Jackson, 1969.
3. Hoffman and Walker, 1978, analysis 6-7-8, p. 705.
4. Onyeagocha, 1974, analysis 2-4A#1.
5. Bliss and MacLean, 1975, analysis 17, p. 977.
6. Ulmer, 1974.
7. Pinsent and Hirst, 1977, analysis 60186(F), p. 589.

**Table 10.** Chemical analyses of ultramafic rocks near monzonite dike at the Highline claim

[In weight percent]

Sample -----	LC-7	LC-4	LC-5	LC-10	LC-9	LC-6
Distance from dike -----	10 cm	0.5 m	3 m	13 m	18 m	45 m
SiO <sub>2</sub> -----	49.8	47.0	42.9	45.4	39.9	42.3
Al <sub>2</sub> O <sub>3</sub> -----	5.5	6.7	5.4	4.1	2.1	4.4
Fe <sub>2</sub> O <sub>3</sub> -----	6.0	7.7	8.1	7.3	6.9	6.8
FeO -----	4.0	4.2	6.3	6.2	1.1	3.9
MgO -----	19.7	18.8	26.8	28.3	36.8	29.7
CaO -----	11.2	10.0	4.0	3.0	.43	4.7
Na <sub>2</sub> O -----	.71	.75	.20	.26	.00	.07
K <sub>2</sub> O -----	.16	.11	.05	.07	.03	.04
H <sub>2</sub> O <sup>+</sup> -----	.95	.80	4.1	3.8	11.3	6.0
H <sub>2</sub> O <sup>-</sup> -----	.25	.19	.24	.20	.64	.34
TiO <sub>2</sub> -----	.17	.22	.24	.22	.07	.15
P <sub>2</sub> O <sub>5</sub> -----	.03	.03	.03	.03	.02	.04
MnO -----	.20	.23	.16	.15	.08	.07
CO <sub>2</sub> -----	.05	.03	.12	.14	.02	.13
Cr <sub>2</sub> O <sub>3</sub> -----	--	2.8	--	--	--	--
Total	98.72	99.56	98.64	99.17	99.39	98.64

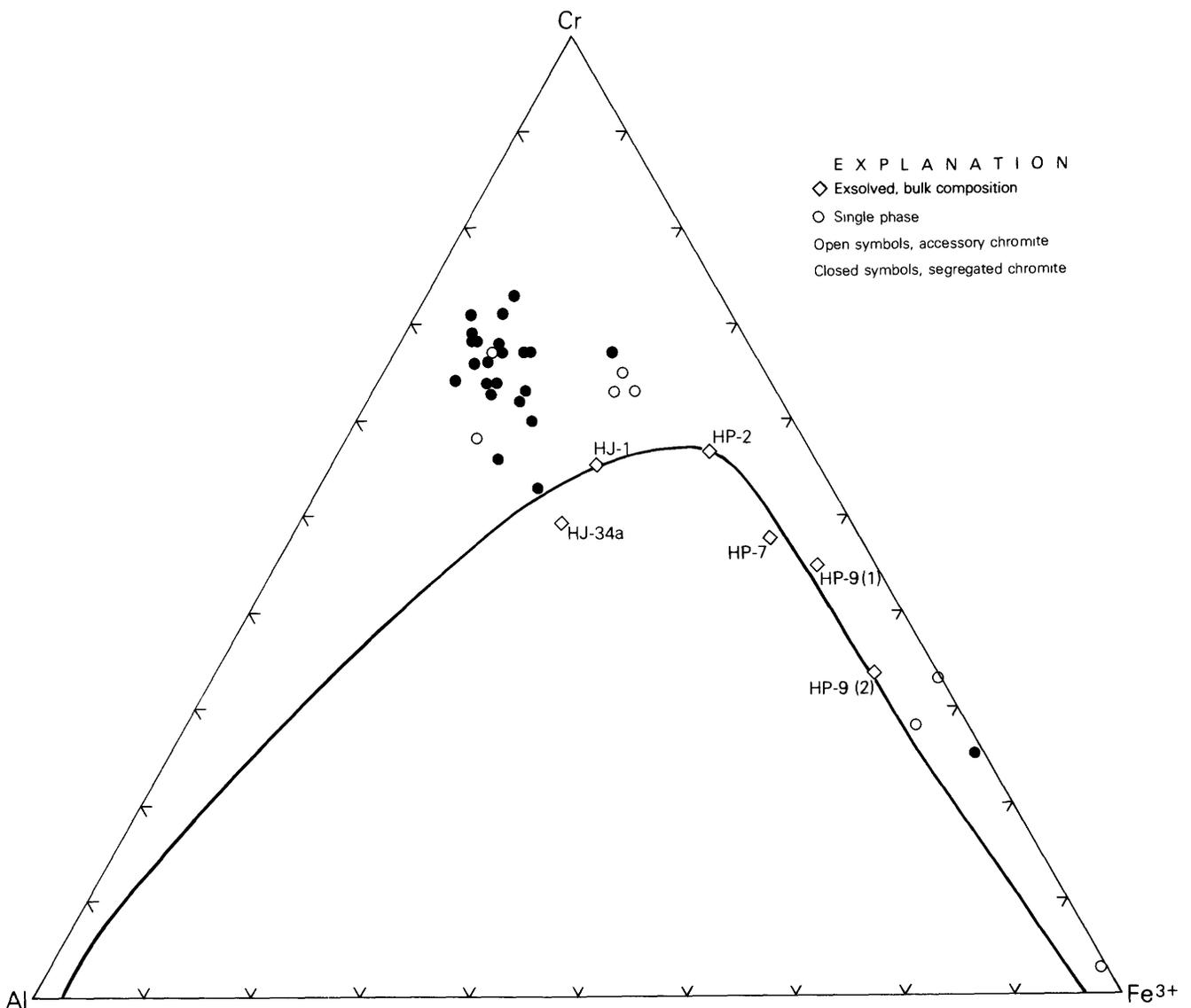


Figure 17. Chromite compositions with respect to Cr-Al-Fe<sup>3+</sup>, showing the solvus as defined by exsolved pairs.

nearby Highline Trail Lakes area (Skinner, 1969). The compositions of some of the Red Lodge chromites correspond to those from stratiform intrusions. In addition, the segregated chromites in the Red Lodge ultramafics are relatively fine grained and many have chain textures that are similar to textures of chromite from stratiform complexes (Thayer, 1960; Jackson, 1961). Finally, the age and geologic setting of the Red Lodge rocks are similar to those of other stratiform deposits.

Thus, tectonic disruption of a stratiform intrusion appears to be the most likely origin of the Red Lodge ultramafic lenses. The diversity of rock types, and the different chromite compositions in the various deposits occur because the lenses are fragments from various levels in the parent stratiform mass. Tectonic emplacement of the ultramafic lenses is implied by their sheared contacts against the coun-

try rocks. The diverse metamorphic assemblages are the result of alteration of feldspathic and nonfeldspathic parent rocks, and the chromite, although now altered, probably showed primary compositional differences between the various layers, which are still detectable (see fig. 15). Associations of mafic rocks and small bodies of ultramafic rocks in high-grade metamorphic terrains similar to that of the Red Lodge area have been described by other workers (Bowes and others, 1964; Bowes and others, 1966; Girardi and Ulbrich, 1980). The origins have variously been interpreted as tectonic disruption of a stratiform complex (Bowes and others, 1964; Bowes and others, 1970), and as fractional crystallization of olivine-tholeiite magma to produce a series of ultramafic rocks and a magma residue which formed associated gabbroic rocks, all of which underwent tectonic disruption (Girardi and Ulbrich, 1980).

Other workers have recognized two contrasting types of metamorphosed layered complexes: anorthosite-leucogabbro complexes such as the Fiskenaeset of Greenland (Windley and others, 1981) and ultramafic-gabbro complexes such as those in northwest Scotland (Bowes and others, 1964) and southern Africa (Robertson, 1973). The Red Lodge rocks are similar to the latter type, and in fact the

geologic setting in the Beartooth Mountains appears to be like that in the Archean craton of Zimbabwe. The Great Dyke (relatively unaltered and intact) has a Rb-Sr age of  $2,510 \pm 20$  m.y. and is flanked by older, altered, chromite-bearing ultramafic complexes with a Nd-Sm age of  $2,640 \pm 140$  m.y. (see, for example, Wilson, 1968; Hamilton, 1977; and Hamilton and others, 1977).

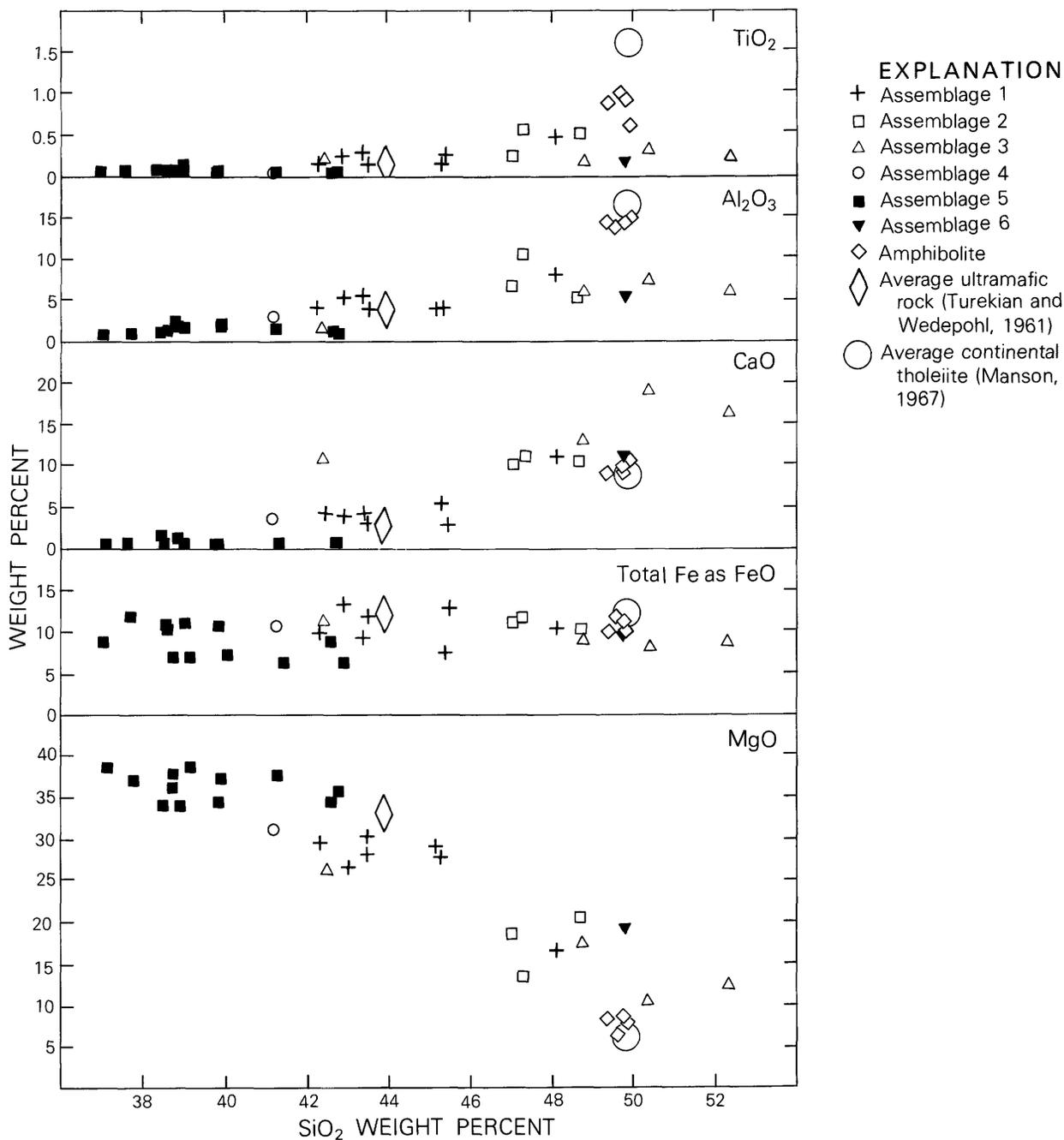
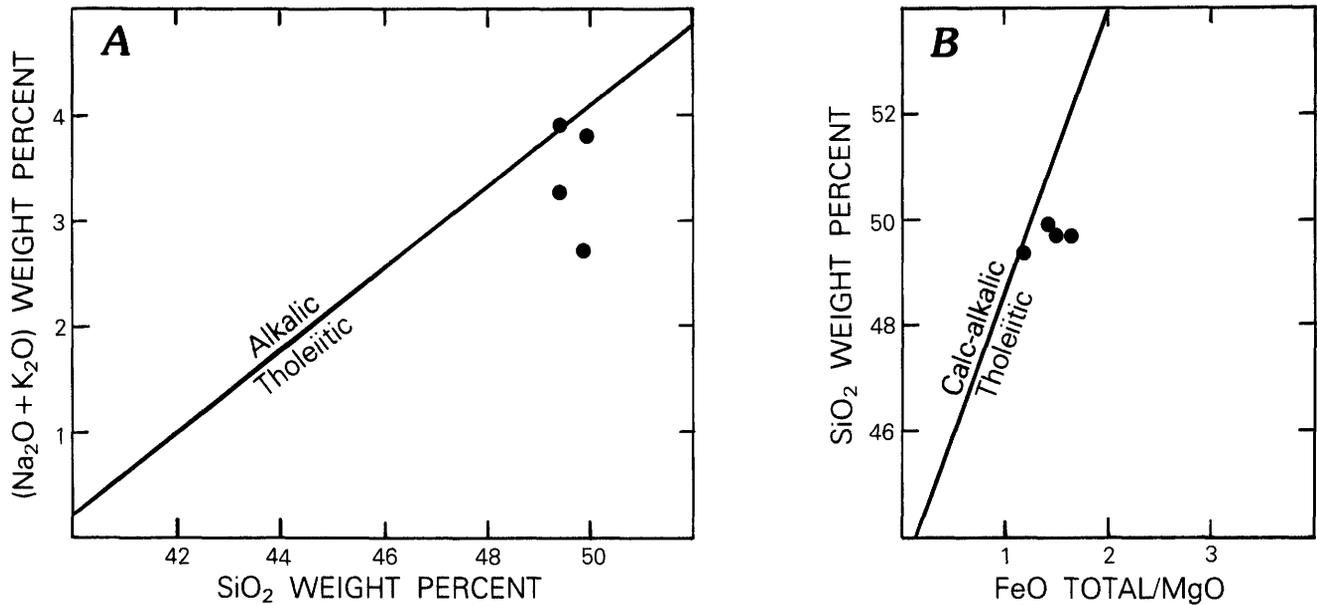


Figure 18. Variation diagrams of selected oxides versus  $\text{SiO}_2$  in ultramafic rocks and amphibolites from the Red Lodge district.

**Table 11.** Chemical and normative analyses of Red Lodge rocks, and comparative averages  
 [Analyses by Judy Reid and Hezekiah Smith of the U.S. Geological Survey]

Sample Location	Assemblage 1 HP-19 Gallon Jug 1	Assemblage 2 HP-16 Gallon Jug 2	Assemblage 3 HP-2 Drill	Assemblage 4 SR-2 Four Chromes	Assemblage 5 HP-11 North Star	Assemblage 6 LC-7 Highline	Average ultramafic rock	Average continental tholeiite <sup>2</sup>
<b>Oxides, weight percent</b>								
SiO <sub>2</sub>	43.5	47.3	52.4	41.1	36.9	49.8	43.88	49.9
Al <sub>2</sub> O <sub>3</sub>	4.4	10.3	6.3	3.2	.59	5.5	3.78	16.2
Fe <sub>2</sub> O <sub>3</sub>	6.6	3.2	3.1	6.5	7.7	6.0	--	3.0
FeO	5.9	9.1	6.1	5.0	2.0	4.0	12.13	7.8
MgO	30.2	13.2	12.0	30.3	38.1	19.7	33.82	6.3
CaO	3.0	11.6	16.4	3.6	.75	11.2	3.50	9.8
Na <sub>2</sub> O	.13	1.1	1.2	.17	.01	.71	.57	2.8
K <sub>2</sub> O	.09	.85	.77	.05	.01	.16	< .01	1.1
H <sub>2</sub> O <sup>+</sup>	5.2	.94	.32	7.9	10.1	.95	--	1.0
H <sub>2</sub> O <sup>-</sup>	.25	.16	.25	.18	.64	.25	--	--
TiO <sub>2</sub>	.17	.54	.20	.09	.03	.17	.05	1.6
P <sub>2</sub> O <sub>5</sub>	.07	.05	.08	.01	.02	.03	.05	.30
MnO	.20	.21	.38	.13	.07	.20	.21	.17
CO <sub>2</sub>	.04	.02	.03	1.4	1.6	.05	--	--
<b>Total</b>	<b>99.8</b>	<b>98.6</b>	<b>99.5</b>	<b>99.6</b>	<b>98.5</b>	<b>98.7</b>	<b>98.0</b>	<b>100.00</b>
<b>Normative mineralogy, weight percent</b>								
Q	--	--	1.01	--	--	--	--	--
C	--	--	--	--	0.52	--	--	--
Or	0.53	5.10	4.57	0.30	.06	6.05	--	--
Ab	1.10	9.45	10.20	1.44	.09	6.09	--	--
An	11.18	20.98	9.58	7.85	--	8.96	--	--
Ne	--	--	--	--	--	--	--	--
Wo	1.26	15.45	29.84	.47	--	19.57	--	--
En	41.83	20.48	30.03	41.40	30.93	41.64	--	--
Fs	3.04	8.45	9.06	2.14	--	2.10	--	--
Fo	23.53	9.04	--	24.07	44.18	5.68	--	--
Fa	1.89	4.11	--	1.37	--	.32	--	--
Mt	9.59	4.71	4.52	9.46	6.69	8.82	--	--
Hm	--	--	--	--	3.21	--	--	--
Il	.32	1.04	.38	.17	.06	.33	--	--
Ap	.17	.12	.19	.02	.05	.07	--	--
Cc	.09	.05	.07	3.20	1.31	.12	--	--
Mg	--	--	--	--	2.00	--	--	--
<b>Total</b>	<b>94.53</b>	<b>98.98</b>	<b>99.45</b>	<b>91.89</b>	<b>89.09</b>	<b>99.75</b>	<b>98.0</b>	<b>100.00</b>

<sup>1</sup> From Turekian and Wedepohl, 1961. <sup>2</sup> From Manson, 1967.



**Figure 19.** Compositional plots of amphibolites, indicating mostly tholeiitic compositions. A, SiO<sub>2</sub> versus (Na<sub>2</sub>O+K<sub>2</sub>O) in weight percent. B, FeO total/MgO versus SiO<sub>2</sub> in weight percent.

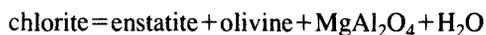
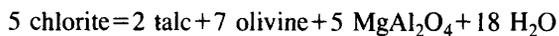
## FORMATION AND POST-EMPLACEMENT HISTORY

The following sequence of events is proposed for the genesis of the Red Lodge ultramafic rocks:

1. A layered igneous intrusion is formed and includes dunite, peridotite, feldspathic peridotite, pyroxenite, and gabbro, with local concentrations of chromite.

2. Some rocks are partially or completely serpentinized, and magnetite rims form on the chromite.

3. The rocks undergo upper amphibolite facies regional metamorphism, tectonic disruptions, and emplacement of various fragments of the layered intrusion. At low grades, chromite reacts with magnetite rims to form Fe-rich, Mg- and Al-depleted homogeneous ferritchromite. At high grades, above the break down of chlorite, chromite reacts and is enriched in the MgAl<sub>2</sub>O<sub>4</sub> component. Possible reactions are:



(Evans and Frost, 1975). Chromite of various compositions undergoes the various types of exsolution between Al-rich and Fe-rich end members. Olivine, enstatite, and hornblende are formed at the highest grades, with the various assemblages controlled by the original mineralogy.

4. Some of the rocks undergo retrograde metamorphism, probably controlled by the availability of H<sub>2</sub>O. Serpentinization and limited formation of talc, chlorite, phlogopite, carbonate minerals, and magnetite occur. Magnetite rims form on some chromite, and Al-rich chromite is altered to ferritchromite+chlorite; otherwise the chromite is not affected.

5. The rocks are subjected to low-grade metamorphism possibly corresponding to the 1,600–1,800 m.y. event (Nunes and Titton, 1971; Rowan and Mueller, 1971); there is limited recrystallization of serpentine (lizardite → antigorite) and formation of lizardite hour-glass textures.

## ECONOMIC GEOLOGY

The United States is entirely dependent on foreign sources for chromite, which is the only ore mineral of chromium. Chromium is an indispensable industrial metal, used primarily as a component of stainless steel to increase the hardness, strength, and resistance to corrosion, a use for which there is presently no known substitute. It is used in the chemical industry, in tanning leather, in pigment, and for plating, and the mineral chromite is used as a refractory in high-temperature metallurgical furnaces (Thayer, 1973; Thayer and Lipin, 1978). Most of the U.S. supply of chromite is imported from southern Africa, Turkey, the Philippines, and the USSR. Together, the Bushveld Complex of South Africa and the Great Dyke of Zimbabwe

**Table 12.** Trace-element analyses of Red Lodge ultramafic rocks

[Spectrographic analyses by Norma Rait of the U.S. Geological Survey.; ppm, parts per million; ppb, parts per billion; n.d., not determined]

	Cr (ppm)	Co (ppm)	Ni (ppm)	Sc (ppm)	Pt (ppb)	Pd (ppb)	Rh (ppb)
<b>Rocks containing accessory chromite</b>							
Assemblage 1							
HP-20A -----	5,000	250	1,200	28	< 3	5	1
HP-24 -----	2,400	200	1,800	19	< 4	3	< 1
LC-5 -----	2,200	210	1,000	30	< 2	4	1
Assemblage 2							
HP-8 -----	1,000	170	670	51	n.d.	n.d.	n.d.
Assemblage 3							
HP-1 -----	3,600	110	910	12	< 3	2	< 1
HP-27 -----	4,100	200	740	32	10	22	1
Assemblage 4							
SR-2 -----	7,100	290	1,200	25	< 4	11	< 1
Assemblage 5							
HP-9 -----	6,400	120	1,400	5	n.d.	n.d.	n.d.
HP-11 -----	7,100	190	2,300	5	< 3	8	1
HP-14 -----	n.d.	n.d.	n.d.	n.d.	< 1	< 2	< 1
HP-29 -----	11,000	250	2,100	9	14	48	2
LC-11 -----	3,100	110	1,400	10	n.d.	n.d.	n.d.
<b>Rocks containing segregated chromite</b>							
Assemblage 2							
LC-15 -----	n.d.	n.d.	n.d.	n.d.	< 2	< 1	6
Assemblage 4							
HP-31 -----	n.d.	n.d.	n.d.	n.d.	18	6.4	13
LC-13 -----	n.d.	n.d.	n.d.	n.d.	< 2	< 1	4
Assemblage 5							
HP-10A -----	n.d.	n.d.	n.d.	n.d.	< 2	< 1	7
HP-30 -----	n.d.	n.d.	n.d.	n.d.	< 2	< 1	8
<sup>1</sup> Goles, 1967 -----	2,400	110	1,500	16			
<sup>2</sup> Turekian and Wedepohl, 1961 -----	170	48	130	30			

<sup>1</sup> Average for ultramafic rocks from Goles, 1967.<sup>2</sup> Average for basaltic rocks from Turekian and Wedepohl, 1961.

contain an estimated 99 percent of the worldwide chromite resources (Thayer and Lipin, 1978).

Within the United States, about 80 percent of the chromite resources occur in the Stillwater Complex. Most of the remainder is in small podiform deposits scattered in the mountain belts on the east and west coasts (Thayer, 1973), especially in Oregon and California. All U.S. deposits are low grade, and are not currently economic. However, it is

of interest to assess the economic potential of the deposits, such as those at Red Lodge, because production of chromite from domestic sources may be necessary in the future, in the event of a disruption of foreign sources.

Most of the known massive chromite has already been mined from the Red Lodge deposits. About 77,000 tons of ore, averaging 12.8 percent Cr<sub>2</sub>O<sub>3</sub>, remains in the deposits (Simons and others, 1979), and about 100,000 tons of

undiscovered ore probably remains in the area (James, 1946). The present study shows that the concentration of chromite in the rocks ranges from 1 percent to about 80 percent, but is mostly between 5 and 15 percent.

The compositions of the chromite have been altered by metamorphism, and this will affect their future economic potential. Some segregated chromites have compositions similar to magmatic chromite from stratiform intrusions. Other segregated chromites and most accessory chromites have metamorphic compositions, and the general trend of alteration is toward Fe-enrichment and Mg- and Al-depletion. Ferritchromit is formed by this chemical alteration and commonly occurs as homogenous grains, less commonly as partial rims on chromite, and as fine intergrowths with chlorite(?) as an alteration of Al-rich chromite. Accessory chromite is generally more highly altered than segregated chromite.

This study has shown that the composition of the chromite is related to the metamorphic silicate assemblage. In general, hornblende-rich rocks contain chromite of somewhat higher Fe content than other rocks. Serpentinites contain chromite of slightly lower Fe content, but contain other Fe-rich phases such as magnetite and ferritchromit. Ferritchromit-chlorite intergrowths that occur as alteration products of Al-rich accessory chromite in some of the serpentinites may present sliming problems in milling disseminated ore. The rocks that contain orthopyroxene have two coexisting chromites of Fe- and Al-rich compositions, and late-stage serpentinization produces the ferritchromit-chlorite type of alteration of the Al-rich chromites.

The present study has shown that the Red Lodge ultramafic rocks probably are parts of a disrupted stratiform complex. If this is correct, there may be more chromite deposits in fragments of the stratiform complex concealed at various depths below the surface. Aeromagnetic surveys conducted by Simons and others (1979) indicate both small and large magnetic anomalies in the present study area and in other areas throughout the Beartooth Mountains. Those authors concluded that the anomalies were caused by concealed intrusive bodies. The magnetic anomaly caused by the ultramafic rocks of the Stillwater Complex is similar in magnitude to the other anomalies in the Beartooths. Therefore, it is possible that some of the anomalies are caused by buried ultramafic to mafic rocks.

Magnetometer surveys conducted in the Red Lodge area by James (1946) showed that the ultramafic rocks produced anomalies, and that chromite ore bodies produced anomalies of even greater magnitude. James (1946) concluded that local anomalies near some of the ultramafic lenses were produced by other concealed ultramafic rocks.

However, even if concealed deposits are in the area, the chromite would probably have compositions similar to those in the exposed deposits, and their economic potential would thus be hindered by the same factors: (1) the high-Fe compositions; (2) the presence of abundant magnetite as

grains, veins, and rims on accessory chromite in serpentinites; (3) ferritchromit-chlorite(?) intergrowths in serpentinized rocks.

Other elements of possible economic interest include the platinum group elements (PGE), cobalt, and nickel. This study has shown that the concentration of PGE's in the Red Lodge ultramafic rocks is one to two orders of magnitude lower than that in the nearby Stillwater Complex (Page and others, 1969). The economic potential of PGE's from the Red Lodge rocks is, therefore, very low.

Likewise, the amounts of cobalt and nickel are about an order of magnitude lower than the amounts that are currently economic. In general, only the nickel in sulfides is recoverable. The Red Lodge samples contain only small amounts of sulfides, including a Ni-Fe sulfide associated with serpentinized samples. The bulk of the nickel is in chromite and in the silicates, where it is not recoverable by present means. It is not known which minerals contain the cobalt in the Red Lodge samples because cobalt contents were not determined for individual mineral species.

## CONCLUSIONS

A petrologic study was made of upper-amphibolite facies chromite-bearing ultramafic rocks that occur as small lenses in the Red Lodge chromite district, Montana. Results indicate:

1. All chemical and mineralogical evidence shows that the deposits are not alpine-type. The ultramafic lenses are probably fragments of a stratiform complex that was tectonically disrupted and emplaced during the metamorphism. This interpretation is consistent with the stratiform-type compositions of some segregated chromite, the relatively fine grain size of the chromite and absence of nodules, the Archean age, and the geologic environment.

2. Accessory chromite shows a greater degree of chemical alteration than segregated chromite.

3. In the highest grade orthopyroxene-bearing rocks, green Al-rich chromite was formed, and it coexists with Fe-rich chromite. In other rocks, the general trend of chromite alteration is toward the formation of homogeneous ferritchromit through Fe-enrichment, and Mg- and Al-depletion. This adversely affects the economic potential of the chromite remaining in the deposits.

4. If it is necessary to produce chromite from the deposits in the future, the following should be considered. Most of the massive chromite has already been mined from the Red Lodge deposits. Accessory chromite is ubiquitous in the ultramafic rocks, but drawbacks to its economic potential include the high-Fe metamorphic compositions; the presence of magnetite as grains, veins, and rims on chromite in serpentinites; ferritchromit-chlorite(?) intergrowths as alteration products of Al-rich

chromite in serpentized rocks, which may cause problems in milling.

5. Cobalt, nickel, and the Pt-group elements are all present in amounts well below current economic limits.

## REFERENCES

- Armbrustmacher, T. J., and Simons, F. S., 1977, Geochemistry of amphibolites from the central Beartooth Mountains, Montana-Wyoming: U.S. Geological Survey Journal of Research, v. 5, p. 53–60.
- Aumento, F., 1970, Serpentine mineralogy and ultramafic intrusions in Canada and on the mid-Atlantic Ridge: Geological Survey of Canada Paper 69–53.
- Beeson, M. H., and Jackson, E. D., 1969, Chemical composition of altered chromites from the Stillwater complex, Montana: American Mineralogist, v. 54, p. 1084–1100.
- Bence, A. E., and Albee, A. L., 1968, Empirical correction factors for the electron microanalysis of silicates and oxides: Journal of Geology, v. 76, p. 382–403.
- Best, M. G., 1974, Mantle-derived amphibole within inclusions in alkalic-basaltic lavas: Journal of Geophysical Research, v. 79, p. 2107–2113.
- Bliss, N. W., and MacLean, W. H., 1975, The paragenesis of zoned chromite from central Manitoba: Geochimica et Cosmochimica Acta, v. 39, p. 973–990.
- Bowes, D. R., and Skinner, W. R., 1969, Geochemical comparison of the Stillwater complex and alpine-type ultrabasic complexes, Beartooth Mountains, Montana and Wyoming: Geological Magazine, v. 106, no. 5, p. 477–484.
- Bowes, D. R., Skinner, W. R., and Wright, A. E., 1970, Petrochemical Comparison of the Bushveld igneous complex with some other mafic complexes: Geological Society of South Africa, Special Publication 1, p. 425–440.
- Bowes, D. R., Wright, A. E., and Park, R. G., 1964, Layered intrusive rocks in the Lewisian of the North-West Highlands of Scotland: Quarterly Journal Geological Society of London, v. 120, p. 153–192.
- 1966, Origin of ultrabasic and basic masses in the Lewisian: Geological Magazine, v. 103, p. 280–283.
- Butler, J. R., 1969, Origin of the Precambrian granitic gneiss in the Beartooth Mountains, Montana and Wyoming, in *Igneous and metamorphic geology*: Geological Society of America Memoir, v. 115, p. 73–101.
- Casella, C. J., 1964, Geologic evolution of the Beartooth Mountains, Montana and Wyoming. Part 4. Relationship between Precambrian and Laramide structures in the Line Creek area: Geological Society of America Bulletin, v. 74, p. 969–986.
- 1969, A review of the Precambrian geology of the eastern Beartooth Mountains, Montana and Wyoming, in *Larsen, L. H., Prinz, Martin, and Manson, Vincent, Igneous and Metamorphic geology*: Geological Society of America Memoir, v. 115, p. 53–71.
- Chidester, A. H., 1962, Petrology and geochemistry of selected talc-bearing ultramafic rocks and adjacent country rocks in north-central Vermont: U.S. Geological Survey Professional Paper 345, 207 p.
- Coleman, R. G., 1977, Ophiolites, in *Wyllie, P. J., ed., Minerals and rocks*, v. 12: Heidelberg, Springer-Verlag, 229 p.
- Cressy, B. A., 1979, Electron microscopy of serpentine textures: Canadian Mineralogist, v. 17, p. 741–756.
- Dungan, M. A., 1979, A microprobe study of antigorite and some serpentine pseudomorphs: Canadian Mineralogist, v. 17, p. 771–784.
- Eckelmann, F. D., and Poldervaart, Arie, 1957, Geologic evolution of the Beartooth Mountains, Montana and Wyoming, Part 1. Archean history of the Quad Creek area: Geological Society of America Bulletin, v. 68, p. 1225–1262.
- Evans, B. W., 1977, Metamorphism of alpine peridotite and serpentinite: Annual Review of Earth and Planetary Sciences, 5, p. 397–447.
- Evans, B. W., and Frost, B. R., 1975, Chrome-spinel in progressive metamorphism—a preliminary analysis: Geochimica et Cosmochimica Acta, v. 39, p. 959–972.
- Francis, D. M., 1976, The origin of amphibole in lherzolite xenoliths from Nunivak Island, Alaska: Journal of Petrology, v. 17, p. 357–378.
- Gast, P. W., Kulp, J. L., and Long, L. E., 1958, Absolute age of early Precambrian rocks in the Bighorn Basin of Wyoming and Montana, and southeastern Manitoba: American Geophysical Union Transactions, v. 39, p. 322–334.
- Girardi, V. A. V., and Ulbrich, H. H. G. J., 1980, Origin and evolution of the Pien mafic-ultramafic complex, Southern Brazil: Journal of Geology, v. 88, p. 251–269.
- Goles, G. G., 1967, Trace elements in ultramafic rocks, in *Wyllie, P. J. ed., Ultramafic and related rocks*: New York, John Wiley and Sons, Inc., p. 352–362.
- Hamilton, P. J., 1977, Sr isotope and trace element studies of the Great Dyke and Bushveld mafic phase and their relation to early Proterozoic magma genesis in southern Africa: Journal of Petrology, v. 18, p. 24–52.
- Hamilton, P. J., O’Nions, R. K., and Evensen, N. M., 1977, Sm-Nd dating of Archean basic and ultrabasic volcanics: Earth and Planetary Science Letters, v. 36, p. 263–268.
- Hess, H. H., 1955, Serpentinities, orogeny, and epeirogeny, in *Poldervaart, Arie, ed., Crust of the Earth*: Geological Society of America Special Paper 62, p. 391–408.
- Hey, M. H., 1954, A new review of the chlorites: Mineralogical Magazine, v. 30, p. 277–292.
- Himmelberg, G. R., and Coleman, R. G., 1968, Chemistry of primary minerals and rocks from the Red Mountain-Del Puerto ultramafic mass, California: U.S. Geological Survey Professional Paper 600–C, p. C18–C26.
- Hoffman, M. A., and Walker, D., 1978, Textural and chemical variations of olivine and chrome spinel in the East Dover ultramafic bodies, south-central Vermont: Geological Society of America Bulletin, v. 89, p. 699–710.
- Irvine, T. N., 1965, Chromian spinel as a petrogenetic indicator, Part 1. Theory: Canadian Journal of Earth Sciences, v. 4, p. 71–103.
- 1967, Chromian spinel as a petrogenetic indicator, Part 2. Petrologic applications: Canadian Journal of Earth Sciences, v. 4, p. 71–103.
- Jackson, E. D., 1961, Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana: U.S. Geological Survey Professional Paper 358, 106 p.

- 1969, Chemical variation in coexisting chromite and olivine in chromitite zones of the Stillwater complex in Magmatic ore deposits, a symposium: *Economic Geology Monograph 4*, p. 41–71.
- James, H. L., 1946, Chromite deposits near Red Lodge, Carbon County, Montana: U.S. Geological Survey Bulletin 945-F, p. 151–189.
- Leake, B. E., 1978, Nomenclature of amphiboles: *American Mineralogist*, v. 63, p. 1023–1052.
- Lipin, B. R., 1980, Metamorphic vs. magmatic chromite in North Carolina dunites and some economic implications [abs.]: *Geological Society of America Abstracts with Programs*, v. 12, p. 472.
- Loferski, P. J., 1980, Unusual exsolution in metamorphosed chromite from the Beartooth Mountains, Montana [abs.]: *Geological Society of America Abstracts with Programs*, v. 12, p. 472.
- Loferski, P. J., and Lipin, B. R., 1983, Exsolution in metamorphosed chromite from the Red Lodge district, Montana: *American Mineralogist*, v. 68, p. 777–789.
- Manson, V., 1967, Geochemistry of basaltic rocks—Major elements in basalts, in Hess, H. H., and Poldervaart, Arie, eds., *Basalts—the Poldervaart treatise on rocks of basaltic composition*: New York, Interscience Publication, v. 1, p. 215–269.
- Muir, T. L., 1979, Discrimination between extrusive and intrusive Archean ultramafic rocks in the Shaw Dome area using selected major and trace elements: *Canadian Journal of Earth Sciences*, v. 16, p. 80–90.
- Muir, J. E., and Naldrett, A. J., 1973, A natural occurrences of two-phase chromium-bearing spinels: *Canadian Mineralogist*, v. 11, p. 930–939.
- Nunes, P. D., and Tilton, G. R., 1971, Uranium-lead ages of minerals from the Stillwater complex and associated rocks, Montana: *Geological Society of America Bulletin*, v. 82, p. 2231–2250.
- Onyeagocha, A. C., 1974, Alteration of chromite from the Twin Sisters dunite, Washington: *American Mineralogist*, v. 59, p. 608–612.
- Page, N. J., 1979, Stillwater Complex, Montana—structure, mineralogy, and petrology of the Basal zone with emphasis on the occurrence of sulfides: U.S. Geological Survey Professional Paper 1038, 69 p.
- Page, N. J., Engin, T., Haffty, J., 1979, Palladium, platinum, and rhodium concentrations in mafic and ultramafic rocks from the Kizildag and Guleman areas, Turkey, and the Faryab and Esfandagheh-Abdasht areas, Iran: U.S. Geological Survey Open-File Report 79-840, 15 p.
- Page, N. J., Myers, J. S., Haffty, Joseph, Simon, F. O., and Aruscavage, P. J., 1980, Platinum, palladium, and rhodium in the Fiskenaesset Complex, Southwest Greenland: *Economic Geology*, v. 75, p. 907–915.
- Page, N. J., Riley, L. B., and Haffty, Joseph, 1969, Platinum, palladium, and rhodium analyses of ultramafic and mafic rocks from the Stillwater Complex, Montana: U.S. Geological Survey Circular 624, 12 p.
- Papike, J., Cameron, K., and Baldwin, K., 1974, Amphiboles and pyroxenes: characterization of *other* than quadrilateral components and estimates of ferric iron from microprobe data [abs.]: *Geological Society of America Abstracts with Programs*, v. 6, p. 1053–1054.
- Phillips, T. L., Loveless, J. K., and Bailey, S. W., 1980, Cr<sup>3+</sup> coordinating chlorites: a structural study of ten chromian chlorites: *American Mineralogist*, v. 65, p. 112–122.
- Pinsent, R. H., and Hirst, D. M., 1977, The metamorphism of the Blue River ultramafic body, Cassier, British Columbia, Canada: *Journal of Petrology*, v. 18, p. 567–594.
- Poldervaart, Arie, 1958, Ultramafic rocks in Highline Lakes area, Beartooth Mountains, Wyoming [abs.]: *Geological Society of America Bulletin*, v. 69, p. 1630.
- Robertson, I. D. M., 1973, The geology of the country around Mount Towla, Gwanda district: *Rhodesian Geological Survey Bulletin*, v. 68, 168 p.
- Rowan, L. C., and Mueller, P. A., 1971, Relations of folded dikes and Precambrian polyphase deformation, Gardner Lakes area, Beartooth Mountains, Wyoming: *Geological Society of America Bulletin*, v. 82, p. 2177–2186.
- Simons, F. S., Armbrustmacher, T. J., Van Noy, R. M., Zilka, N. T., Federspiel, F. E., Ridenour, James, and Anderson, L. A., 1979, Mineral resources of the Beartooth Primitive Area and vicinity, Carbon, Park, Stillwater, and Sweet Grass Counties, Montana, and Part County, Wyoming: U.S. Geological Survey Bulletin 1391-F, 125 p.
- Skinner, W. R., 1969, Geologic evolution of the Beartooth Mountains, Montana and Wyoming. Part 8. Ultramafic rocks in the Highline Trail Lakes area, Wyoming: *Geological Society of America Memoir*, v. 115, p. 19–52.
- Springer, R. K., 1974, Contact metamorphosed ultramafic rocks in the western Sierra Nevada foothills, California: *Journal of Petrology*, v. 15, p. 160–195.
- Stosch, H. G., and Seck, H. A., 1980, Geochemistry and mineralogy of two spinel peridotite suites from Dreiser Weiher, West Germany: *Geochimica et Cosmochimica Acta*, v. 44, p. 457–470.
- Terry, R. D., and Chillingar, G. V., 1955, Summary of “Concerning some additional aids in studying sedimentary formations” by M. S. Shvetsov: *Journal of Sedimentary Petrology*, v. 25, p. 229–234.
- Thayer, T. P., 1960, Some critical differences between alpine-type and stratiform peridotite-gabbro complexes: *International Geological Congress 21st, Copenhagen 1960*, Rept. XIII, p. 247–259.
- 1967, Chemical and structural relations of ultramafic and feldspathic rocks in alpine intrusive complexes, in Wyllie, P. J. ed., *Ultramafic and related rocks*: New York, John Wiley and Sons, Inc., p. 222–239.
- 1970, Chromite segregations as petrogenetic indicators: *Geological Society of South Africa Special Publication 1*, p. 380–389.
- 1973, Chromium, in Brobst, D. A., and Pratt, W. A., eds., *United States Mineral Resources*: U.S. Geological Survey Professional Paper 820, p. 111–121.
- Thayer, T. P., and Lipin, B. R., 1978, A geological analysis of world chromite production to the year 2000 A.D.: *Council of Economic A.I.M.E. Proceedings*, 107th meeting., p. 143–146.
- Turekian, K. K., and Wedepohl, K. H., 1961, Distribution of the elements in some major units of the earth's crust: *Geological Society of America Bulletin*, v. 72, p. 175–192.

- Ulmer, G. C., 1974, Alteration of chromite during serpentinization in the Pennsylvania-Maryland district: *American Mineralogist*, v. 59, p. 1236-1241.
- Whittaker, E. J. W., and Zussman, Jack, 1956, The characterization of serpentine minerals by X-ray diffraction: *Mineralogical Magazine*, v. 31, p. 109-126.
- Wicks, F. J., 1979, Mineralogy, chemistry, and crystallography of chrysotile asbestos, in Ledown, R. L., ed., *Short Course in Mineralogical Techniques of Asbestos Determination*: Mineralogical Association of Canada Short Course 4, p. 35-75.
- Wicks, F. J., and Plant, A. G., 1979, Electron-microprobe and X-ray-microbeam studies of serpentine textures: *Canadian Mineralogist*, v. 17, p. 785-830.
- Wicks, F. J., and Whittaker, E. J. W., 1977, Serpentine textures and serpentinization: *Canadian Mineralogist*, v. 15, p. 459-488.
- Wilson, J. F., 1968, The geology of the country around Mashaba: *Rhodesia Geological Survey Bulletin* 62, 239 p.
- Windley, B. F., Bishop, F. C., and Smith, J. V., 1981, Metamorphosed layered igneous complexes in Archean granulite-gneiss belts: *Annual Review of Earth and Planetary Science*, v. 9, p. 175-198.



